A CRITICAL ANALYSIS OF RESEARCH DONE TO IDENTIFY CONCEPTUAL DIFFICULTIES IN ACID-BASE CHEMISTRY

by

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As the candidate's supervisor I have approved this dissertation for submission.

Signed: ______________________ Name: __________________ Date: ________

PREFACE

The research described in this dissertation was carried out in the Science Education Research Group (SERG), Discipline of Biochemistry, School of Biochemistry, Genetics and Microbiology, University of KwaZulu-Natal (Pietermaritzburg campus), from April 2001 to April, 2009 under the supervision of Professor Trevor R. Anderson.

These studies represent the original work by the author and have not otherwise been submitted in any form for any degree or diploma to any other university. Where use has been made of the work of others, it has been duly acknowledged in the text.

Sheelagh Edith Halstead (Candidate)

Prof Trevor R. Anderson (Supervisor)

April 2009

DECLARATION 1 – PLAGIARISM

I, Sheelagh Edith Halstead, declare that

1. The research reported in this dissertation, except where otherwise indicated, is my original research.
2. This dissertation has not been submitted for any degree or examination at any other university.
3. This dissertation does not contain other persons' data, pictures, graphs or other information unless specifically acknowledged as being sourced from other persons.
4. This dissertation does not contain other person's writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:
    a. Their words have been re-written but general information attributed to them has been referenced,
    b. Where their exact words have been used, then their writing has been placed in quotation marks or indented and referenced.
5. This dissertation does not contain text, graphics or tables copied and pasted from the internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References section.

Signed: ______________________________ Date: ____________

DECLARATION 2 – PUBLICATIONS

Details of contributions to publications that form part and include research presented in this dissertation: The research presented in the following three papers was conceptualized, planned, executed and written-up by the candidate, Sheelagh E. Halstead, who in each case is reflected as the first author. Anderson (Supervisor) and Spankie (Co-supervisor for the initial part of the study) performed the expected supervisory duties which included facilitating the performance of the research, engaging in regular discussion and deep conceptual debate with the candidate about the work and assisting in the editing of the final manuscripts.

Publication 1:

Halstead, S. E., Anderson, T.R. & Spankie, S. (2002). Student difficulties with different models in acid-base chemistry. In C. Malcolm & C. Lubisi (Eds) *Proceedings of the South African Association for Research into Mathematics, Science and Technology Education Annual Conference, January 2002 Durban,* South Africa.

Publication 2:

Halstead, S. E., Anderson, T.R. & Spankie, S. A. A. (2003). Formulation of statements of propositional knowledge and corresponding student difficulties for the Brønsted-Lowry acid-base model: A reciprocal matching and honing process. In D. Fisher & T. Marsh (Eds), *Proc. 3rd Conference on Science, Mathematics and Technology Education* (Vol. 1, pp 377-388). East London, South Africa: Curtin University

Publication 3:

Halstead, S. E. & Anderson, T. R. (2009) *What can we learn from studies on students' conceptual difficulties? The case of propositional knowledge of acid-base models.* In Press to 17th Annual Conference of the South African Association for Research into Mathematics, Science and Technology Education, Grahamstown, South Africa 2009

Signed: ____________________________

For Stewart

This has been an important part of the healing process.

“We sometimes hear ... that this viewpoint is perhaps not correct, but only a useful working, substituting working hypothesis. This objection is in fact not an objection at all, for we can never be certain that we have found the ultimate truth.” Arrhenius (1903)

“Perfection is rare in the science of chemistry. Our scientific theories do not spring full-armed from the brow of the creator. They are subject to slow and gradual growth.” (Lewis, 1906)

ABSTRACT

The literature review shows that student alternative conceptions or misconceptions are important for teaching and learning. Causes of such student difficulties may include the counter-intuitive nature of some chemistry concepts or to instruction itself. However, over 30 years research into student conceptual difficulties has had little impact on teaching and learning chemistry. In this study, a critical analysis and synthesis of published research into student conceptions in acid-base chemistry was carried out in the naturalist nomothetic paradigm using a constructivist framework. Historical models which were included were an operational macroscopic model and the theoretical Arrhenius and Brønsted models. Firstly, a comprehensive search strategy with defined inclusion/exclusion criteria identified 42 suitable reports which were mostly peer-reviewed. The identified research was not limited to Anglophone countries although Africa and South America were underrepresented and research among secondary students predominated. Then a critique of the research showed it was of variable quality and often poorly reported. An outcome was a set of guidelines for research into student conceptions. The variable quality and reporting of research then also necessitated a four-level framework to reflect the stability of descriptions of student difficulties. A new method for synthesis of descriptions of student conceptual difficulties was developed which entailed mapping qualitative data on the difficulties, which had been extracted from research publications, to propositional knowledge statements derived in this study. This was an iterative process which simultaneously honed descriptions of difficulties and illuminated propositional knowledge implicated in them. The second major outcome was synthesized descriptions of 10 student difficulties with acid-base species, 26 difficulties with acid-base properties and 17 difficulties concerning terminology and symbolism particular to acid-base chemistry. Some conceptions were also found to have been mis-reported as ‘misconceptions’. The difficulties could be broadly due to student conceptions concerning acid-base models, or students not relating empirical observations to theoretical models or their poor understanding of underlying chemical principles. Some difficulties were found to have been over-researched, while further work was needed to clarify the nature some difficulties with conceptions of bases, acid-base reactions, and symbolism used in acid-base chemistry. The third major outcome from the synthesis was 218 propositional knowledge statements which were shown to be suitable for teaching high-school students, avoided hybrid historical models and were acceptable to expert chemists. These propositional statements were integrated as a set of 11 concept maps. The maps showed the hierarchy and interconnectedness of concepts as well as the propositional links which had been implicated in the difficulties. Furthermore the concept maps indicated critical concepts where teaching in each topic should focus as well as cross-linked concepts that can be used to integrate different aspects of the topic. Accordingly they contribute to PCK in the acid-base topic as they represent the fine-grained yet well integrated conceptual knowledge characteristic of a teacher with highly developed PCK.

ACKNOWLEDGEMENTS

I had been teaching high school science for some years when in the course of teaching a Grade 8 class about ‘being a scientist’, one girl asked “but when do you get a chance to do your experiments?” This set me to question myself about how I could call myself a scientist if I didn’t actually do science. Tarryn, you will never know what a life-changing process you started. From that conversation I realised that I wanted to progress into chemistry education research. When shortly afterwards an opportunity arose to study towards a higher degree in this field, I jumped at it.

Firstly, acknowledgement must go to my supervisor, Professor Trevor Anderson for his drive in putting in place the chance for me to undertake the research. Trevor, your patience and unwavering belief in my ability, as you mentored me through the minefield of unfamiliar terminology and formal academic writing, has kept me going. The enthusiasm you showed for my work is contagious; I would not have found the stamina to continue through ill-health and other setbacks without this. It is hard to express adequate appreciation.

I also extend thanks to Dr Sally Spankie for her input concerning early parts of the project. I am so sorry you were unable to continue in this role. More latterly I acknowledge the valuable input from Drs Colin Southway and Jennifer McKenzie. The work was also made possible through a research grant from the National Research Foundation (NRF: GUN Number 2053218) in South Africa.

Many colleagues have also been an integral part of my work. Those in the Science Education Research Group (SERG) may not realise how much the stimulation of working with them has meant to me. I vividly recall my excitement after the first meeting, and the realisation of how happy this had made me. Added to this are the lifelong friendships formed. To Lynn du Plessis in particular, thank you for being my shoulder to lean on when needed; we have shared so many joys and frustrations in the process of working towards higher degrees. My other friends and colleagues, firstly at Epworth School and more latterly in the Centre for Science Access, have also given me unwavering support and understanding. Thank you all.

It is impossible to thank my family enough for the way they have constantly bolstered me up, practically and emotionally. You have made so many sacrifices as you allowed me to complete this research project. To Mum, your tacit acknowledgement of how important this undertaking was for me and so taking responsibility for practical details in daily life which I was unable to fulfil, is so appreciated. To my sisters, you have all kept me going by email and phone, and then in the latter stages, helping with editing, checking and numerous cups of tea. To my daughter Avril, I have loved talking through some of the academic issues with you, and my infinite thanks for teaching me how to format with styles.

Finally to my husband Dave, you have made the most sacrifices, taking on so much of the housekeeping, cooking so many meals, and calming me down over technical hitches with computers. But more than anything, thank you for your patience and kindness, reminding me to keep focused, and allowing me to put my needs ahead of your own on so many occasions. Maybe now we can get back to normality.

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CHAPTER 1

INTRODUCTION AND AIMS OF THE STUDY

Student difficulties with learning science have produced a considerable body of research spawned by Driver and Easley's seminal work in 1978 (Driver & Easley, 1978). Early studies focused on student preconceptions in physics leading to a concept inventory test (Hestenes *et al.*, 1992), with later work in biology (e.g. Lawson & Thompson, 1988), chemistry (Taber, 2002) and latterly biochemistry (Grayson *et al.*, 2001). However, this research has not yet effected substantially improved teaching and learning of science (Osborne, 1996; Erickson, 2000) although various causes for conceptual difficulties have been cited. These include naïve preconceptions (Benson *et al.*, 1993), 'misconceptions' relating to ideas that contradict empirical facts (Herron, 1996), student reasoning strategies (Stavy & Tirosh, 2000; Talanquer, 2006) and even instruction itself (Taber, 2001a). Furthermore, difficulties in chemistry have been attributed to three levels of representation, namely macroscopic, sub-microscopic and chemical symbolism, which students need to understand and distinguish but simultaneously integrate (Johnstone, 2002). Different models of representations abound in theoretical chemistry (Hoffman & Laszlo, 1999) and incorrect teaching of scientific models has been implicated in student conceptual difficulties (Justi & Gilbert, 1999; Taber, 2001a). Furthermore, textbooks have been implicated in this problem, particularly in acid-base chemistry (e.g. Furió-Más *et al.,* 2005), but they remain a primary resource for teachers (Costa *et al.,* 2000; Drechsler & Schmidt, 2005a). Despite a need for textbook revision, few reviews of research into student conceptual difficulties in chemistry have been published; some have been general (Garnett *et al.*, 1995; Kind, 2004) while others are topic specific (e.g. Çalyk *et al.*, 2005a), but acid-base chemistry has received little attention. Moreover, there has been little method development for this type of synthesis (Liu, 2001).

I knew from ten years experience in high school teaching that acid-base chemistry was a challenging topic. I thought it was due to student confusion over acid-base definitions as well as poor understanding of sub-microscopic processes. When an opportunity arose for research, I wanted to contribute something useful for teachers which would increase their pedagogical content knowledge or PCK. PCK involves transforming content of a discipline to make it suitable for teaching. It includes knowledge of ways to represent and organise ideas and potential cognitive challenges for students (Shulman, 1986). Accordingly I hypothesized that critical analysis (as review and synthesis) of existing research on conceptual difficulties in acid-base chemistry would also highlight corresponding conceptual knowledge that should be made explicit for students. This led to the following specific research questions and sub-questions, designed to review, critique and synthesise published research.

1) *What is the nature of research published on student difficulties with acid-base chemistry?*
    a) *Which reports give suitable research data on student conceptual difficulties in acid-base chemistry?*
    b) *What is the scope of this research?*
    c) *What is the overall quality of this research?*
2) *What difficulties do students experience with species in acid-base chemistry?*
    a) *What descriptions of difficulties with acid-base species can be synthesised from existing research data?*
    b) *How stable are these difficulty descriptions across different contexts?*
    c) *What statements of propositional knowledge are needed to address difficulties with species in acid-base chemistry?*
3) *What difficulties do students experience with acid-base properties?*
    a) *What descriptions of difficulties with acid-base properties can be synthesised from existing research data?*
    b) *How stable are these difficulty descriptions across different contexts?*
    c) *What statements of propositional knowledge are needed to address difficulties with acid-base properties?*
4) *What difficulties do students experience with terminology and symbolism in acid-base chemistry?*
    a) *What descriptions of difficulties with acid-base terminology and symbolism can be synthesised from existing research data?*
    b) *How stable are these difficulty descriptions across different contexts?*
    c) *What statements of propositional knowledge are needed to address difficulties with acid-base terminology and symbolism?*
5) *Does the set of propositional knowledge statements derived through analysis of student difficulties reflect appropriate knowledge for teaching and learning acid-base models?*
    a) *How well do the propositional statements reflect curriculum models for acid-base chemistry?*
    b) *What are the implications of the propositional knowledge for teaching and learning acid-base chemistry?*

The structure of this dissertation in addressing these research questions is outlined in Figure 1.1 and then described briefly.

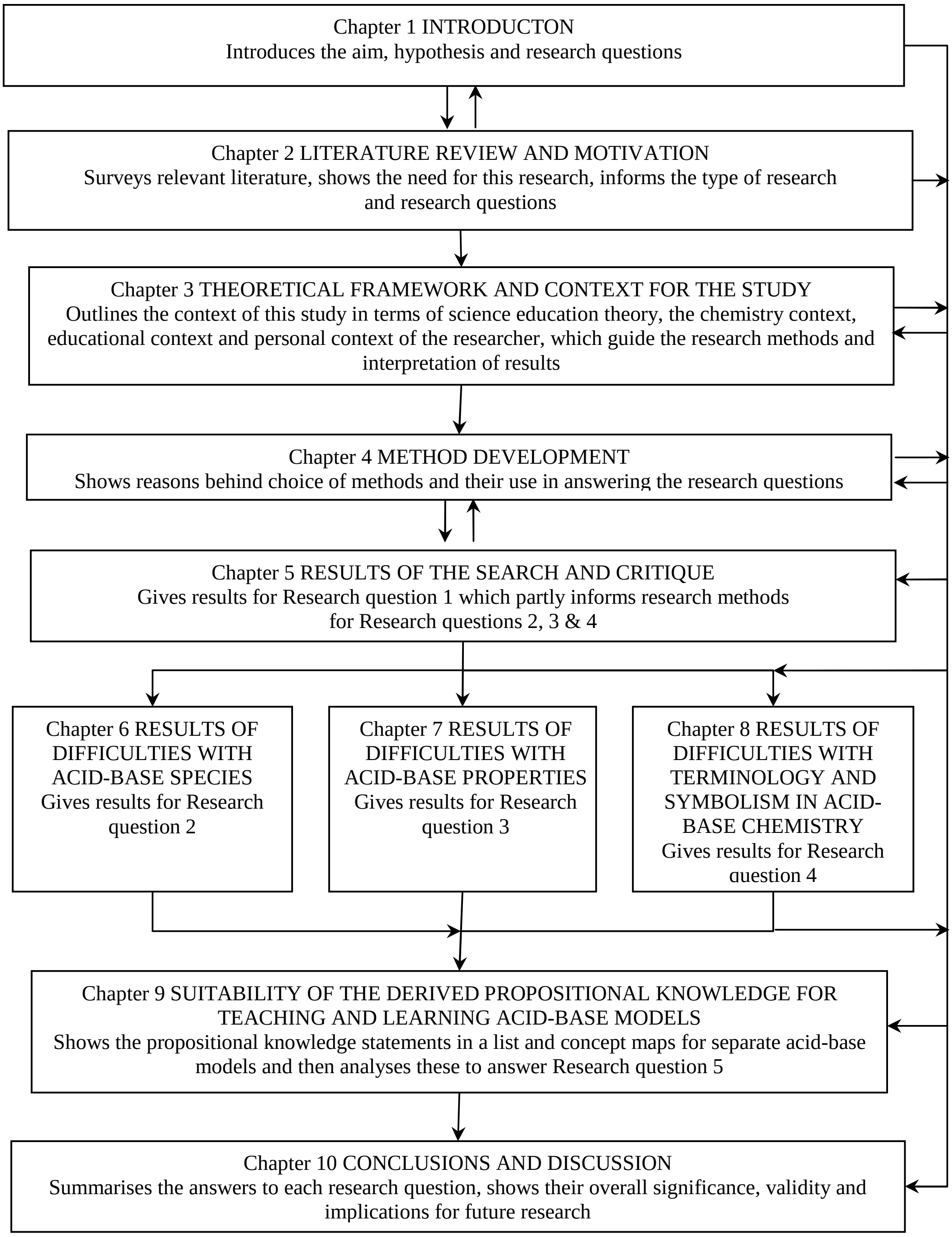

Figure 1.1 Flow diagram to show structure of the dissertation

The first research question asked *What is the nature of research published on student difficulties with acid-base chemistry?* It was addressed through a process of comprehensively searching and rigorously screening relevant literature against a set of criteria which I had previously developed (sub-question 1a). Then the overall scope of the research was analysed according to different variables (sub-question 1b). Finally there was a critique of the research (sub-question 1c). The methods by which these were carried out are given in Chapter 4, with results of this process being given in Chapter 5.

Three parallel questions were asked in Research questions 2, 3 and 4. Firstly, Research question 2 asked *What difficulties do students experience with species in acid-base chemistry?* It was addressed by synthesising descriptions indicating commonalities behind evidence from independent research projects – this was Research question 2a. Sub-question 2b necessitated evaluating the stability of each difficulty description across different educational and chemistry contexts according to a four-level framework. To this end, results from the critique of original research according to Research question 1 were used. The method used for synthesising descriptions simultaneously revealed propositional knowledge necessary to answer sub-question 2c. Individual propositional statements were extracted from publications by experts in chemistry and chemistry education; textbooks were a minor source. The need for each propositional statement was largely intuitive, according to my teaching experience. The applicable method for each sub-question is described in Chapter 4 with results being given in Chapter 6. This chapter starts with a table showing relevant difficulties together with propositional statements implicated in each. The difficulties are then discussed individually to show how the descriptions and propositional statements were derived.

Answering Research questions 3 and 4 entailed parallel research processes to those used for Research question 2. Respectively, the two questions were *What difficulties do students experience with acid-base properties?* and *What difficulties do students experience with terminology and symbolism in acid-base chemistry?* Results for these questions are presented in Chapters 7 and 8 respectively, using a similar format to Chapter 6.

The last research question was *Does the set of propositional knowledge statements derived through analysis of student difficulties reflect appropriate knowledge for teaching and learning acid-base models?* To answer this question, criteria for acceptable propositional statements had first been developed before deriving the propositional statements used to answer to Research questions 2, 3 and 4. Then a composite list of all the propositional statements was arranged in a conceptual hierarchy derived from a set of concept maps. The propositional statements and concept maps were examined together against criteria to ensure their suitability for teaching and learning in order to consider their appropriateness for high school teaching, consistency with acid-base models and acceptability to expert chemists (sub-question 5a). Further analysis of the propositional statements and concept maps alongside the difficulties addressed sub-question 5b. Criteria for propositional statements and methods used for constructing concept maps are outlined in Chapter 4 Results, including a table of all propositional statements and concept maps, are given in Chapter 9.

In the last chapter findings from all five research questions are summarised, their limitations evaluated and implications discussed. Finally the implications of all the findings for both educational practitioners and researchers are considered with a view to future research.

The research process involved much cross referencing between three tables of criteria, critique of original research reports and the theoretical framework for the chemistry context, so relevant tables have been presented in a flip-out out form, enabling a reader to consult several aspects at the same time. A list of research reports used in the synthesis is given in Appendix 1, page 272, in addition to their citation as general references.

CHAPTER 2

LITERATURE REVIEW AND MOTIVATION FOR THE STUDY

Learning a body of knowledge accepted by scientists can present difficulties for novices. This chapter looks initially at the nature of such knowledge. It then gives some possible sources for conceptual difficulties that students may experience when they come to learn this body of knowledge. Next this chapter gives some criticisms of research into student difficulties and why this body of work has not effected significant changes in teaching and learning science. Some research deficiencies are identified and recommendations made for the type of analysis that is needed. This literature review does not focus on acid-base literature because this literature is the focus of the main research study.

2.1 CONSTRUCTS OF SCIENCE KNOWLEDGE

2.1.1 Scientific Concepts

Rule-governed scientific concepts may be “deliberately and consciously invented or adopted for a special scientific purpose” (Kerlinger, 1986, p 27). Scientific concepts always include a definition; this statement of critical attributes of a concept tells us which characteristics are individually necessary and jointly sufficient to classify instances as examples or non-examples (Smith & Medin, 1981; Herron, 1996). Thagard (1996, p 60) terms critical attributes “default expectations”. Several definitions may pertain to one concept, and in a physics context, Galili and Lehavi (2006) include both operational and instrumental definitions (indicating how to measure a quantity) alongside theoretical definitions. However, definitions are only one aspect of the set of knowledge that should be associated with a concept label and overemphasising them could suggest erroneously that concepts are single units of knowledge, rather than networks (Pines, 1985; Herron, 1996).

Networks of knowledge can be organised around concepts (Novak, 2002). Concepts are abstractions or generalizations linked by a particular label, which could be its name or a symbol (Kerlinger, 1986; Novak, 1996). White and Gunstone (1992, p 85) advance an idea of a concept being the “total set of knowledge associated with a label”. Pines (1985, p108) terms it a “locus of meaning” associated with a concept label – a meeting place of all relationships associated with the concept label. Concepts may derive from events or objects with perceived shared characteristics, which are then generalized as a class or set of examples (Novak, 1985). The context or framework in which a concept is used may determine which relationships are indicated by its label (Pines, 1985; Kellogg, 2003); for example, a concept of *matter* as a continuous matrix of grains or drops (as a *finite element*) would be quite acceptable in materials science, whereas chemists conceive matter to be made up of discrete atoms and molecules (Andersson, 1990). Furthermore, an everyday concept and a scientific concept may share a label, which is a possible source of confusion for students (Pines & West, 1986).

Concepts bring order to the world (Smith & Medin, 1981) as they may be organised hierarchically (Thagard, 1996). A concept's position in a hierarchy of associated concepts (super-ordinate, co-ordinate or supra-ordinate) is part of the set of knowledge associated with a concept (Herron, 1996). In addition to critical attributes given in a concept definition, Herron also includes attributes that may vary across examples of concepts. While limited examples, as stereotypes or prototypes, may be adequate for everyday concepts, a wider range of examples and non-examples need to be associated with a scientific concept in order to indicate both its fullness and limitations. Accordingly, the context specific and hierarchical nature of concepts will influence the manner of presenting propositional knowledge arising from Research sub-questions 2c, 3c and 4c and Research question 5.

2.1.2 Conceptions

Each person's mental representation of a concept is unique and is constantly evolving, through increased variety of examples and an enriched knowledge network. These idiosyncratic personal mental representations of a concept are termed conceptions (Duit & Treagust, 1995). Johansson *et al.* (1985) describe conceptions as a qualitative relationship between an individual and a phenomenon. As part of a conception, White and Gunstone (1992) include propositional knowledge (knowing that), procedural knowledge (knowing how), verbatim learning, images and memories of events, all as parts of conceptual understanding. However, understanding a concept does not necessarily include knowing its label and definition, provided other aspects are present (Herron, 1996; Clerk & Rutherford, 2000). Furthermore, Pines (1985) emphasises that, while a concept itself cannot be judged true or false, the relationships around it may be so judged. Thus a person's conception may differ from consensus ideas of a concept and may include relationships that are at odds with those accepted in a science community. This premise is central to studies on student conceptual difficulties in science. Propositional knowledge is one aspect of a conception that can be compared with consensus scientific knowledge. A proposition's role in linking two concepts is shown by Novak and Gowan (1984), who use a metaphor of concepts being 'atoms' with propositions being 'molecules' from which meaning is built. This study makes use of propositional knowledge indicating a discrete relationship between concepts, which can be compared to student conceptions.

2.1.3 Models

Complementing propositional knowledge, meaningful learning of science involves constructing mental models (Johnson-Laird, 1983; Glynn *et al.*, 1991). These mental models, or inner mental replicas, appear to make use of images (Johnson-Laird, 1983) and have explanatory power. Because they are personal representations (Gilbert *et al*., 2000), it is possible that, like propositional knowledge, mental models may differ from accepted understanding, thus giving rise to misconceptions (Clerk & Rutherford, 2000). Taber (2001a, p 125) argues that, in chemistry, concepts are often not learned hierarchically, because much of the "theoretical content of chemistry is bes*t seen* as a set of models."

Models may be classified according to a typology given by Gilbert *et al.* (2000, pp 12-13). *A consensus model* arises by agreement between different social groups following discussion and experimentation. Once this has "gained acceptance by a community of scientists following formal experimental testing, as manifest by its publication in a refereed journal" it is termed a *scientific model.* If a "consensus model produced in specific historical contexts" is "later superseded for many research purposes" it is called a *historical model.* Students are not yet experts, and a simplified version of an historical or scientific model may be included as a *curriculum model.* Models combining characteristics from individual historical models, using them as a "coherent whole", are termed *Hybrid models.* The present study makes use of this typology of models with regard to student conceptions.

2.2 THE NATURE OF STUDENT CONCEPTUAL DIFFICULTIES

When individuals construct knowledge they do so through a filter of prior knowledge and experience and within their social milieu. The conceptions that students find useful and those reinforced by society will be retained (Mintzes & Novak, 2000; Duit & Treagust, 1995). Student conceptions that differ from those accepted by a community of scientists have generated considerable research in what is known as the Alternative Conceptions Movement (ACM) due to their possible value in planning science instruction (Smith *et al.*, 1993). Early research investigated student naïve preconceptions in mechanics (Lythcott, 1985) and heat (Erickson, 1979). Other disciplines have followed suit, such as research into conceptions of the shape of the Earth (Nussbaum, 1979), of the particle nature of matter **(**Gabel, *et al.*, 1987) or stoichiometry and chemical equilibrium (Huddle & Pillay, 1996). By 1994, Wandersee *et al.* reported over 700 publications on student conceptions in physics and estimated there were 200 investigations of biology conceptions. Research into student biochemical conceptions has been only more recently explored (Grayson *et al*., 2001).

These student conceptions show surprising commonality around the world (Driver, 1995; Solomon, 1993b), being “robust with respect to such factors as age, ability, gender, and culture” (Wandersee *et al*., 1994, p 185). Furthermore, these student conceptions are tenacious – students hold firmly to ideas that appear sensible, unlike simple mistakes (Abimbola, 1988) – and these ideas may persist despite a university education (Pyramid Film & Video, 1988; Evans, 2006). Tenacity of these alternative conceptions has prompted research into specific conceptual change strategies in order to address them (Strike & Posner, 1982; Hewson & Hewson, 1983).

The ACM has spawned much literature but a “plethora of terms” (Wandersee *et al*., 1994, p 178) and lack of uniformity in terminology of the movement are seen as weaknesses in this field of research (Solomon, 1994). In particular, Clerk and Rutherford (2000) criticize some authors for outright failure to define their intended meaning for terms, or for vague generalizations passed off as definitions or for coining yet another new term. Nevertheless, careful choice of terms may indicate two aspects: firstly, it may show an individual research framework – idiographic or nomothetic – and the way in which authors view student conceptions; or it may reflect the type of conception being investigated. These aspects are discussed next.

Within an idiographic framework, researchers may record student conceptions in an ethnographic manner – much as would an anthropologist studying a particular culture. Such work focuses on personal knowledge – what students actually believe – and thus accords respect to these individual conceptions (Lincoln & Guba, 1985; Wandersee *et al*., 1994). This group of researchers would probably use such terms as *children’s science* (Duit & Treagust, 1995), *intuitive conceptions* (Lewis & Linn, 1994), *alternative conceptions* (Hewson, 1985) or *alternative frameworks* (Taber, 2001b).

By contrast, research in a nomothetic (science-centred) framework compares student conceptions with consensus scientific understanding. As a result, there is a hint of judgment that students may be ‘wrong’ (Wandersee *et al*., 1994). Workers from this paradigm are more likely to use the term *misconception* or *pre-conceptions* (Kousathana *et al*., 2005) to describe conceptions or mental models at variance with currently held scientific theory (Clerk & Rutherford, 2000). Such erroneous conceptions could be due to science instruction itself (Duit & Treagust, 1995; Kousathana *et al.*, 2005) or despite good instruction (Driver & Easley, 1978; Kousathana *et al*., 2005). Focusing on missing or faulty connections between concepts resulting in false propositional knowledge, Novak and Gowan (1984) propose the term *Limited or Inappropriate Propositional Hierarchy* (*LIPH*). Being based on the theory of meaningful learning, this term indicates structural weakness in student's mental representations. Accordingly, searching for research published in the field of student conceptions requires an awareness of the variety of terms and, hence, keywords by which authors might describe student conceptions. It also shows that not all authors will be comparing these conceptions to scientifically accepted understanding.

While endorsing the term *LIPH*, Wandersee *et al.* (1994) suggest that the term *misconception* has merits as it is more generally known outside of science education. Furthermore, they are concerned that mainstream scientists, focused on a body of knowledge accepted by consensus, may see little legitimacy in *alternative conceptions*. Mainstream scientists could thus become alienated from work on student conceptions, despite the attention these deserve when teaching. While Herron (1996) acknowledges a negative connotation of the word *misconception*, he maintains that misconceptions are a legitimate and necessary part of intellectual growth. Moreover, he warns: “it is a matter of time before other labels are tainted” (Herron, 1996, footnote p 110). In the same vein, Terry (1993, p 65) had already noted a common view that alternative conceptions are “rather embarrassing ideas conceived on the wrong side of the blackboard.” From this can be seen that, when publicising research on student conceptions to mainstream scientists and teachers (essentially lay-people in the research field), researchers need to be aware of audience perceptions of labels used.

A different approach to terminology is to consider the subject of student conceptions. Are they conceptions of phenomena, explanations of phenomena or scientifically defined concepts? Herron (1996) used *misconception* for student beliefs about phenomena that are contrary to empirical facts; for example, ‘heavier objects will sink in water’. Unlike this example, much early work in the ACM concerned “experience based explanations constructed by a learner to make a range of natural phenomena and objects intelligible”, which Wandersee *et al.* (1994, p 178) term *alternative conceptions.* Examples include conceptions of evaporation (Osborne & Cosgrove, 1983), dissolving (Longden *et al*., 1991) or force (Hestenes, *et al*., 1992). As von

Glasersfeld (1995b) points out, many current textbook explanations may be considered misconceptions in the future. This is shown in the history of science where different models have been proposed to explain or represent the same phenomenon; for instance, Carnot's theory of heat engines in 1824 supposed that 'heat' was conserved, but 40 years later William Thompson proposed that 'energy' was conserved, not heat (Cropper, 2001). These two models might be seen as alternative explanations for the same phenomenon. More recently, in the relatively new field of biochemistry, tertiary and quaternary protein structures remain contentious (Mbewe, 2000). Furthermore, even such a seemingly simple and well-known chemical reaction as the combustion of magnesium in air can provoke disagreement. In this regard, Lee (1999) found only partial consensus among ten university chemistry lecturers over the mechanism by which the reaction occurred – only eight depicted formation of intermediate complexes. So various student generated explanations, which make sense to them, could rightly be termed *alternative conceptions* rather than *misconceptions*.

Scientific concepts are different. Unlike explanations, which may be contentious, scientific concepts are usually agreed on by a community of scientists and defined according to a particular context (see Section 2.1.1). As each concept involves a network of relationships, and a student's conception of a concept may lack some of these or have included them inappropriately, Novak and Gowan's (1984) idea of a *Limited or Inappropriate Propositional Hierarchy (LIPH)* will be used in this study to determine particular network links that might be troublesome. However, some authors claim to have identified 'misconceptions' simply because students could not give an appropriate conceptual label. Clerk and Rutherford (2000) rather classify this as a language difficulty. Similarly, Taber (2001a) distinguishes a situation where a student is not sufficiently familiar with two concepts to be able to distinguish them (a conceptual difficulty) from that where a student merely confuses two labels (a linguistic difficulty). Knowing a concept label does not imply understanding concept and, conversely, not-knowing the label does not imply a misconception. Concept labels are is not the conception of a concept.

Different research positions as indicated by terminology discussed above (alternative conceptions, misconceptions and LIPH) can be seen as complementary features allowing a more inclusive view of the complex process of learning (Duit & Treagust, 1995). In this vein, and avoiding semantic issues, Grayson *et al*. (2001) use the term *student difficulties* to refer to problems that students exhibit in understanding and application of scientific concepts and reasoning skills. This encompasses a broad range of other terms such as alternative conceptions, preconceptions, and incorrect ways of reasoning. This inclusion of reasoning difficulties has since been confirmed by a secondary analysis of published misconceptions in chemistry, which attributed many misconceptions to students' faulty heuristic reasoning (Talanquer, 2006) and confirms the multifaceted nature of learning.

Thus, a student could have a *misconception* in thinking aluminium foil will keep a drink cold, could have an *alternative conception* concerning an explanation for wool keeping drinks warm, and could show a *LIPH* or *misconception* about the scientific meaning of heat capacity. A student may have well-differentiated conceptions of temperature and internal energy of a body without giving these *linguistic* labels; or might be unable to use proportional *reasoning* to calculate the final temperature of a mixture. All of these could be described as *student difficulties* but the distinction in labels is not trivial. Each requires a different didactic means of addressing the problem. The term, *student difficulties,* reflecting a multi-faceted nature of learning science has been adopted in the current project. It will, however, focus on student *conceptual* difficulties, rather than linguistic.

2.3 SOURCES OF STUDENT CONCEPTUAL DIFFICULTIES

Numerous causes have been put forward for student conceptions which are contrary to accepted science. Wandersee *et al*. (1994) warn that tracing the origins of alternative conceptions is largely speculative, as each learner is individual. Nevertheless, the universality of these conceptions among different cultures and ages suggests several common experiences that can cause difficulties. These include the nature of science (and more particularly chemistry) and the language of science, informal and formal instruction, as well as sources within a student, which are discussed below.

2.3.1 The Nature of Science

Students may misunderstand the nature of science (Kousathana *et al.*, 2005). In this way, they may consider scientific conceptions or theories as "a kind of privileged truth" instead of being viable within a historical or practical context (von Glasersfeld, 1995b, p 15). Furthermore, students sometimes believe scientific models have direct correspondence with reality (Oversby, 2000a; Talanquer, 2006). They could be confused between models (Carr, 1984; Hawkes, 1992, Drechsler & Schmidt, 2005b)) and may even attempt to integrate several distinct models into one composite model (Justi, 2000), as do many textbooks (Justi & Gilbert, 1999; 2002a). Teaching a simplified curriculum model may itself introduce difficulties (Glynn *et al.*, 1991).

2.3.2 The Language of Science

The language of science also presents difficulties (Özmen, 2004). Scientific texts often introduce more new vocabulary words per page than do foreign language texts (Glynn *et al.*, 1991). Non-technical words like ‘pungent’ or ‘aqueous’ or ‘excess’ may also be beyond a school pupil’s ordinary vocabulary or not understood within a science context (Cassells & Johnstone, 1983; Johnstone, 1991). Further language difficulties may arise when students superimpose their everyday word associations onto scientific terms with restricted meanings (Pines & West, 1986; Chiu, 2007). Another difficulty may arise when the scientific meaning for a concept label has changed historically, yet the label still invokes the original concept for students (Schmidt & Volke, 2003). Kuhn (1970) argues that this confusion is also found among scientists when a paradigm shift occurs. When students are not learning in their mother tongue, as happens for many in South Africa, these difficulties may be compounded (Moji, 1998). In this matter, Clerk and Rutherford (2000) investigated so called wrong answers to multiple-choice probes published by other authors. They showed these answers had been too readily ascribed to misconceptions (as incorrectly assimilated mental models) rather than language difficulties. They differentiate clearly between these two categories because each requires specific remedial strategies.

Nevertheless, while poor understanding of the language of science may in itself not be a misconception, it can give rise to inappropriate mental models. Herron (1979) believes that when chemistry teachers themselves misuse or permit misuse of scientific language they could contribute to student conceptual difficulties; for instance, allowing students to refer to all of H_2, H^+ and H simply as ‘hydrogen’ suggests erroneously that there is no difference between molecules, ions and atoms. Moreover, knowing the distinctive and limited meanings for explicit terms that are appropriate to specific situations is part of acculturation into chemistry (Oversby, 2000a). Language is one essential level on which to understand and communicate chemistry (Laing, 1999). This language aspect, together with the argument about concept labels from the previous section, is relevant in three ways for the current project; it necessitated a careful analysis of the language used in research instruments and claims of misconceptions but it also informed one of the categories of difficulties.

2.3.3 The Nature of Chemistry

Several levels of thinking characterize, and are the very strength of, modern chemistry as an academic endeavour. These are the macroscopic or operational level, the sub-microscopic or particle level, and then the symbolic level used to describe and explain phenomena. For centuries chemistry was understood only through macroscopic tangible experiences of phenomena. Then by the mid 19th century, symbols, formulae and equations were normal representations among chemists. Much more recently – since 1950 (Laing, 1999) – atoms, electrons and bonding became the dominant way of thinking. Expert chemists move fluently, and sometimes tacitly, between the levels of representation (Johnstone, 1982). By contrast, students have trouble navigating through and integrating the levels (for example Ben-Zvi *et al.*, 1986; Gabel, 1993; Johnstone, 1993; Chiu 2007; Drechsler & Schmidt, 2005b). Johnstone (2002, p11) argues that a reason for these difficulties lies in overload of working memory, which prevents a novice from simultaneously receiving, processing and integrating information in the "triple layer sandwich". Furthermore, an overloaded chemistry curriculum allows students little time to make connections between representational levels, which leaves their knowledge compartmentalized. It then appears that attempting to load too many simultaneous levels of thinking onto students hinders meaningful learning, with resultant conceptual difficulties (Gabel, 1993; Nelson, 2003).

Since 1960, many chemistry courses have *logically* started with elements and atoms, whereas chemistry educators have continually argued against the *psychological* structure of such an inverted highly abstract curriculum (for example Novik & Nussbaum; 1978; Vogelazang, 1987; Gabel, 1989; Johnstone, 1991; Laing 1999; Solomonidou & Stavridou, 2000; Nelson, 2002). Furthermore, Laing (1999) and Johnstone (1991) both maintain that much useful and interesting introductory chemistry can be taught that is both tangible and non-abstract.

Over and above the inherent difficulty of the multi-level nature of chemistry, teachers appear to be unaware of, or may even compound, the problem (Gabel, 1999). In this matter, Loeffler (1989) contends that traditional teaching involves "ambiguously skipping back and forth with an imprecise and often incorrect usage of confusing terms" (p 930). He gives examples of mature chemists frequently using the same word or formula to denote both species (atom, ion or molecule) and substance, assuming that students could infer the intended meaning from the context. Consequently, students, experience difficulties with each representational level, in addition to difficulties in distinguishing, but at the same time linking, these three systems. The difference between knowledge of experts (possibly tacit) and novices forms a large part of the research in this current project.

2.3.4 The Nature of Instruction

Student conceptions are influenced informally by both the media and their peers (Botton, 1995; Chiu, 2007). Solomon (1993a, p 9) describes a "cognitive tension" between cultural and scientific knowledge causing emotional reactions to mask scientific thinking, so that "...what is sensational, or comfortably agreeable, survives at the expense of accuracy." Even a well-educated lay public associates the word *chemical* with manufactured materials, possibly toxic or carcinogenic (Evans, 2006). It is heartening that Longden e*t al.* (1991) report an apparent decrease in this influence as students are exposed to more science instruction.

Formal instruction may cause its own misconceptions. These could arise from teachers' inadequate content knowledge or through inappropriate teaching strategies, or textbooks themselves might foster misconceptions. Teachers' own misconceptions may be transmitted to students (Blosser 1987; Chiu, 2007). Specifically, Kruse and Roehrig (2005) found parallels between scientifically unacceptable conceptions identified among students and their teachers, which were more prevalent among teachers without a chemistry major qualification. The authors concluded that these teachers probably transmitted their own misconceptions to students or covered only superficially content where they lacked confidence. The research also showed that these teachers thought chemistry required much intuitive knowledge, possibly due to their not having experts' tacit way of moving confidently between representation systems in chemistry.

Many chemistry concepts (for example oxidizing agent or proton-donors) are in fact non-intuitive and so students are hardly likely to develop any conceptions (alternative or acceptable) on their own initiative. Taber (2001a, p 128) elaborates (with his own italics): "it is important to note that *most alternative conceptions in chemistry do not derive from the learner's unschooled experience of the world*." In this way he sees alternative ideas, not as naïve or intuitive conceptions such as frequently found in physics, but rather those derived from a student's prior formal learning experiences. Accordingly, he argues that most difficulties in learning chemistry have pedagogic and epistemic causes. Rather than laying blame, Taber asserts that these are opportunities to make things better for students. The aim of this project is to contribute to such a solution.

A connection exists between information available to students and alternative conceptions they might develop; one instance could be a limited range of examples given to students. In particular, if they have studied only strong acids, they might assume that all acids behave similarly (Schmidt, 1997). Another instance could be allowing student conceptions to develop informally, rather than through carefully planned instruction; consequently students may not distinguish between two similar but different concepts (Herron; 1996; Taber, 2001a). As discussed earlier, Herron (1996) suggests that before teaching a topic, teachers first undertake a conceptual analysis, which includes finding examples and non-examples to show the extent and limitations of a concept.

There could also be a mismatch between students' prior learning and teachers' assumptions about students' existing ideas. Students' pre-existing conceptual links are critical for meaningful learning so conceptual problems may easily arise when teachers falsely assume that a student understands core concepts and make no provision for this knowledge to be constructed (Tullberg, 1994). Without tacit knowledge which experts use to weave their way through different representational models in chemistry, students could well have limited or inadequate conceptions. Identifying this tacit knowledge as propositions (see Section 2.1.2) is the focus of Research sub-questions 2c, 3c and 4c.

Textbooks may also be a source of misconceptions due to a mismatch between scientifically accurate models or theories and those that are appropriate to the cognitive development of younger students. It is impractical to teach a sophisticated expert view to young children, but presenting a simpler, more easily comprehended theory (as a curriculum model, see Section 2.1.3) may result in actually teaching misconceptions. If these are not subsequently straightened out they may be carried through as scientific illiteracy (Glynn *et al.*, 1991). Over-simplistic textbooks which introduce errors are a widespread problem shown, for example, in research from physics (Carvalho & Sampaio, 2006), biology (Clifford, 2002) and chemistry (Sanger & Greenbowe, 1999; Smith & Jacobs, 2003). The problem is found among elementary textbooks, as shown by Barrow (2000), and those for university undergraduates, as shown by Sawyer (2005). In particular, textbook presentation of scientific models has been widely criticized as confusing for students (e.g. Carr, 1984; Loeffler, 1989; Oversby, 2000a; de Vos & Pilot; 2001; Drechsler & Schmidt, 2005a; Justi & Gilbert, 1999, Gilbert *et al.*, 2000). More specifically, Andersson (1986) recommends that textbooks emphasise the provisional nature, as well as explanatory and predictive roles of models, while making clear distinctions between a model and the real world: “If our ideas about atoms are correct what should happen here?” (p 561). In both this review article and another in 1990, Andersson emphasises careful choice of words; for example, water is frequently described as consisting of oxygen and hydrogen conveying an idea that it is a mixture, rather than being described as a compound of oxygen and hydrogen. Accordingly, in the current project, propositional knowledge which was put forward, needed to be carefully verified, to make it compatible with expert opinion.

2.3.5 The nature of students

According to Brown *et al.* (1989) conceptual knowledge cannot be abstracted from its context, that is, it is situated within the culture in which learning takes place. As this work is situated within a social constructivist paradigm (Novak, 2002), the nature of students is considered to influence their learning. Three aspects are considered here. Students’ gender may affect the type of instruction they need in order to counter misconceptions as, for instance, Chiu’s (2007) evidence for gender differences in conceptual understanding of chemistry among Taiwanese students. In other studies, appropriate interventions enabled females, who initially performed worse than males, to subsequently perform at the same conceptual level as their male peers. These interventions required and assisted students to visualize chemical reactions at particulate levels (Bunce, 2001; Yezierski & Birk, 2006). This suggests that females need specific instruction in using visual models.

Students also tend to compartmentalize their knowledge – using different aspects according to different situations; for instance, Taber (2001a) gives numerous examples where students do not apply electrostatic principles learned in physics to chemical bonding. Students also appear to make little attempt to reconcile everyday and science knowledge, retaining personal theories and models but insulating them for protection from discrepancies observed in science lessons. Personal theories are used out of class while scientific theories are presented for the teacher. However, initial conceptions may be retained but become wrapped up in more and more scientific jargon as students progress, so they are difficult to detect through factual recall tests (Glynn *et al.*, 1991). Lewis and Linn (1994) reported this separation of everyday and science knowledge as occurring among adolescents, adults and even professional scientists. Everyday knowledge as general principles, or p-prims, which students use to predict behaviour of the natural world, may itself not be integrated into a coherent whole, remaining as *knowledge in pieces* (diSessa, 1998), used according to context.

Some students may have difficulty applying rules of logical reasoning. Herron (1996) points out the commonality of proportional relationships in concepts that cause difficulties, for example, density, stoichiometry, acceleration and rate of reaction. Following chains of formal hypothetico-deductive (logical inference such as if... then ...) or probabilistic reasoning have also been put forward as essential reasoning skills for success in science, but which are often lacking (Herron, 1975; Cantu & Herron, 1978; Lawson & Thompson, 1988). The fraction of students identified as having developed such abilities is small: 21% of a biology class with an average age of 13 years (Lawson & Thompson, 1988), 40% of a high school introductory chemistry course (Goodstein & Howe 1978) and 20% of biology students at a community college (Lawson *et al*., 1993). Instead of formal reasoning, students tend to use their own intuitive reasoning rules in mathematics and science (Stavy & Tiroch, 2000). Talanquer (2006) presents a model for interpreting published chemistry misconceptions in terms of students' erroneous ideas which appear to them as 'common sense' and which they use in an attempt to reduce cognitive overload. It is important to identify such troublesome concepts in order to provide appropriate support for such students.

2.4 MOTIVATION FOR A REVIEW OF CONCEPTUAL DIFFICULTIES

Despite the strong message sent by a considerable body of research into student conceptual difficulties in science, there has been criticism that it has had little effect on teaching and learning (e.g. Osborne, 1996; Erickson, 2000; Bennett, Lubben, Hogarth & Campbell, 2005a; Bucat, 2004). The following sections show numerous reasons which have been suggested for this disparity.

2.4.1 Research has to move its focus away from misconceptions

Some authors believe that research should move beyond documenting student difficulties and focus on remediation. Gabel had already claimed in 1993 that there had been sufficient research in chemistry misconceptions and called for more emphasis on moving students forward, when in 2000, Johnstone noted a negative flavour caused by the predominance of research into student misconceptions, with little on how to reverse them. There appeared to have been little change later when Gilbert *et al*. (2002a) continued to decry the preponderance of research from which no development had ensued. Some heed has indeed been paid to these repeated appeals; Tsai and Wen's (2005) content analysis of the main international science education research journals showed there had been a recent drop in the proportion of papers on learning (including conceptions) with a subsequent move towards research in teaching.

Recently there has been revived interest in conceptions research due to a movement towards concept-based learning (Morse & Jutras, 2008). This has prompted development of concept inventories, such as those in mechanics (Hestenes *et al.*, 1992), basic chemistry (Mulford & Robinson, 2002: Potgieter *et al.* 2005), and other disciplines such as biology and biochemistry (Howitt *et al.*, 2008). These inventories of conceptual questions, which rely on established student 'misconceptions' for distractors in multiple-choice items, are well adapted to evaluating pre-knowledge and for teaching large classes, enabling a teacher to respond quickly to students' pre-existing conceptions (Mazur, 1997).

Common student difficulties may also be avoided altogether (e.g. Johnstone, 2002) if educators are aware of them and have well-planned teaching strategies (Schmidt, 1997) (see Section 2.3.4 on chemistry difficulties being largely due to inappropriate instruction). This might involve explicit instruction, especially with non-intuitive concepts (de Vos & Verdonk, 1996), where Muthukrishna *et al*. (1993) claim explicit instruction can be effective in removing 90% of common alternative conceptions. It follows that resurgent interest in conceptions research is prompted by a desire to effect changes as have been called for. Accordingly, accurate descriptions of difficulties are needed. The aim of research questions 2, 3 and 4 is to provide suitable descriptions.

2.4.2 Research should drive changes in teaching

The curriculum and textbooks in chemistry have seen few changes arising from research into student conceptions. An earlier section (2.3.3) on the nature of chemistry highlighted continual but unheeded appeals from science education researchers for a more conceptually appropriate student-centred curriculum. For example, Johnstone (2000) reports that there is more concern about a logical order in which to teach chemistry rather than the psychological principles of learning. More particularly, Schmidt (1995) contends that textbook authors ignored certain misconceptions, yet teachers needed to become aware of these misconceptions if they were to address them. In the same way, Gabel (1999) observed that changes in chemistry textbooks since the 1950s had "not been driven to any great extent by research findings". Moreover, Costa *et al*. (2000) found that teachers most commonly refer to textbooks for information on practical work. So, evidently, a main source of reference for teachers' pedagogical content knowledge (PCK) has not been highlighting research on student conceptions.

2.4.3 Pedagogical Content Knowledge

Pedagogical content knowledge (PCK), as advanced by Shulman (1986), is the form of knowledge that teachers use to transform their specialist content knowledge into suitable learning experiences. It is an amalgam of both subject specific knowledge (the conceptual structure of a subject, the validity of knowledge claims in the subject, and the value of such knowledge) and pedagogical knowledge. Shulman's model of PCK includes the following aspects of making a discipline comprehensible for students:

- The most useful ways to represent ideas;
- The most powerful analogies, illustrations, examples, explanations and demonstrations;
- Knowledge of what makes a topic easy or difficult; that is, knowledge of common preconceptions, alternative conceptions or misconceptions;
- Strategies for organising and understanding ideas.

Further aspects of PCK are evident in recent discussions (Abel, 2008):

- PCK integrates discrete categories of knowledge and applies them synergistically to problems of practice;
- PCK is dynamic; it develops from teacher preparation, experience, and professional development.

Shulman (1987) considers PCK to be an ill-documented source of practice, unlike practice in other professions. Consequently PCK is not easily transmitted to other practitioners (Frappaolo, 2006), although Rollnick *et al*. (2008, p 1366) argue that if it "can be captured and portrayed, it may then be passed on to inexperienced teachers". This has been demonstrated by van Driel *et al*. (2002) where a workshop, based on reported research concerning student difficulties with macroscopic and sub-microscopic levels of representation, proved to be effective in making teachers aware of such difficulties and of ways in which they could help students overcome them.

Classroom experience is currently the primary source of PCK (van Driel *et al*., 2002; Lee & Luft, 2008) but Bucat (2004) is concerned that accumulated PCK does not contribute "to the collective wisdom of the profession" because it disappears when experienced teachers retire.

Like Rollnick *et al.* (2008) above, he recommends that educationalists systematically document the rich pool of experiential PCK, which he believes should then be evaluated formally. This suggestion may not be as simple as it sounds, for two possible reasons. Firstly, rather than being generic, Bucat argues that, in chemistry, PCK is highly specific within a discipline, which implies many interviews to cover even one topic. A second problem became evident in research by Rollnick *et al.* (2008). Through observations they found, as expected, that an experienced teacher displayed highly developed PCK, but they also found that he could not articulate it in an interview. It was tacit, something that he simply did. Therefore recording experienced teachers' PCK could be a laborious process, entailing many observations, interviews or group discussions. Two aspects of PCK are especially relevant in this project. Research into student conceptions from Research questions 2, 3 and 4 could very usefully contribute to teachers' PCK. Another aspect that needs to be captured is subject knowledge of experts which will be included in the propositional knowledge referred to in Research sub-questions 2c, 3c and 4c. As already discussed, what appears to be intuitive knowledge causing difficulties in chemistry could be tacit knowledge among subject experts (see Section 2.3.3).

2.4.4 Teachers should become aware of research

From discussion in Section 2.4.2, teachers' lack of awareness of student conceptual difficulties is no surprise, although it is unfortunate. Furthermore, finding that student misconceptions are shared worldwide can validate much that teachers do, besides fostering their professional development (Osborne, 1996) through increased PCK. Even in 1993, Sanders had highlighted a need for research to be communicated with a target audience of educational practitioners but in 1999 Gabel claimed that nine out of ten instructors were neither aware of common misconceptions, nor of how to counteract them in class. Even much later, Drechsler and van Driel (in press) found that teachers had little knowledge of many student difficulties in acid-base chemistry that had already been published. Moreover, Costa *et al.*'s (2000) study showed that experienced teachers' lack of awareness of science education research findings meant they derived their teaching knowledge instead from experience and 'common sense'. These teachers also did not question this personal knowledge despite research having sometimes challenged its validity. Another concern is that being unaware of potential conceptual difficulties, teachers tended to overestimate their students' performance, as shown by 64% average prediction against 41% performance on conceptual questions (Agung & Schwartz, 2007). Teachers also underestimated how deeply student conceptions were rooted (Salloum & BouJaoude, 2008). It thus appears that teachers are largely unaware of the extent and pervasiveness of student conceptual difficulties. In addition, as discussed earlier, teachers may not be aware that they themselves hold misconceptions, which they may then transmit to students. To be specific, teachers held the erroneous belief that a single atom of sulphur would be a brittle crystalline solid, with the same melting point and density as a sample of sulphur (Kruse & Roehrig, 2005); they also showed little conception of the space occupied by one mole of carbon atoms (Kruse & Roehrig, 2005) or the mass of one atom of hydrogen (Ben-Zvi *et al.*, 1988). Furthermore, teachers sometimes confuse terminology from the macroscopic domain and use it in the sub-microscopic context (de Jong & van Driel, 2001; Kruse & Roehrig, 2005). Nevertheless, reports show that discussion on published misconceptions was a useful and unthreatening way of alerting teachers to their own difficulties (Kruse & Roerig, 2005; Calyk, *et al*. 2005; Drechsler, 2007). Teachers would probably welcome this inclusion: “I know chemistry, but knowing and teaching are two different things” (Kruse & Roehrig, 2005, p 1248). It appears that teachers are not resistant to and would in fact welcome this knowledge about student difficulties.

Publishing for teachers is not the same as publishing for a research community; teachers find much science education research unwieldy. Costa *et al.* (2000) appeal to researchers to elaborate findings so as to make them relevant for teaching practice. This is echoed in Gilbert *et al.*’s (2002a) plea for such potentially relevant findings to be made accessible in professional journals for chemistry teachers. All too often research remains published only in journals (Jenkins; 2000) or remains unpublished in theses and dissertations (Anderson, pers. com.) where it is then forgotten. Teachers’ workload is such that they have little time to read and work out applications for research findings; instead they need ready-made solutions to specific classroom difficulties which they encounter (Anderson, 2007). As de Jong (2004) observes: “The key problem here is that teachers expect research to be presented to them in a form they can readily apply because they are too busy doing their job to read the research literature.” However, researchers’ careers often depend on publications in peer-reviewed journals, which may cause a divide between research and practice (de Jong, 2005). Nevertheless, there has been some progress in making research findings available for educators. In this regard, an analysis of main science education journals by Viglietta (1996) showed that many were trying to address the problem of bridging research and practice, for example, adopting a more magazine-like format to some sections or inviting authors to write educator-centred articles such as the series: “Bridging the education research – teaching practice gap” (Anderson & Schönborn, 2007; 2008; Schönborn & Anderson, 2008a; 2008b). Attempts have also been made to publicize this research in a suitable form through websites, for example, Anderson and McKenzie (2002), see CARD at http://www.card.unp.ac.za. These efforts to publicize the considerable body of research on student difficulties appear to be a start in effecting changes in teaching strategies.

2.4.5 The nature of research already conducted

Numerous criticisms of the nature of research on student conceptions have been made. Some research has been of low quality or poorly reported (Eybe & Schmidt, 2001). It has also been described as lacking replication studies (Sanders, 1993; Wandersee *et al.*, 1994; Krnel *et al.*, 1998; Jenkins, 2000; Grayson *et al.*; 2001; Kind, 2004). Both aspects have resulted in dismally slow progress in developing accurate descriptions of specific student difficulties (Grayson *et al.*, 2001). As already noted, Clerk and Rutherford (2000) believe that different types of difficulties require different strategies to counter or avoid them. We need to know what we are addressing before we address it. It follows that coherent, focused and effective research giving greater insight into the nature of student conceptions is needed in order to plan effective remedial or preventative action.

Some gaps in the research field of misconceptions have been identified within specific topics (Garnett *et al*., 1995; Erickson, 2000), which researchers need to fill so as to provide necessary insight into student conceptions. Furthermore student conceptions in some topics have been over-researched (Grayson *et al.*, 2001) and for these Gabel's (1993) call to move forward should be heeded. In this regard, Tsai and Wen's (2005) content analysis of science education research journals gives few instances of recent review papers in any field of science education. Some general reviews of student difficulties have been published in journals (Driver & Easley, 1978; Garnett *et al*., 1995), in handbooks (Gabel & Bunce, 1994; Wandersee *et al*, 1994), or electronically (Kind, 2004). Latterly reviews have become more focused. Examples covering student conceptions in chemistry include: conceptions of matter (Andersson, 1990; Krnel *et al*. 1998), solutions and dissolving (Çalyk, *et al.*, 2005a), stoichiometry (Furió *et al.*, 2002), and chemical bonding (Özmen, 2004; Ünal *et al*., 2006). Research question 1 of the current project will include a review of the scope of existing research.

Systematic reviews of uncoordinated research could well provide a bridge between research and practice. These systematic reviews, as advocated by Gilbert *et al.* (2002a), differ from traditional review articles. Criticisms of traditional narrative reviews include authors' complete, and possibly subjective, discretion over inclusion or exclusion of material, sometimes with no explicit assessment of research quality (Bennett *et al*., 2005a). Moreover, traditional reviews may be biased towards larger studies published in top journals, while neglecting smaller but important studies (Torgerson, 2003). The 'streamlined' systematic review process which Bennett *et al*. (2005a) advocate is suitable for a narrowly focused research question to be answered through secondary analysis of published research reports. It has rigorous and replicable strategies for searching, screening and mapping these reported studies. Adapted from medical research, it has proved effective in science education (Bennett, Campbell, Hogarth & Lubben, 2005b; Lubben *et al.,* 2005; Bennett *et al.,* 2007) but it seems, at the time of writing, that it has not been used for research into student conceptions.

2.4.6 Propositional knowledge in conceptions research

When Erikson (2000, p 287) advocated further research on domains where knowledge of student conceptual difficulties was lacking, he emphasised a need to include "explicit orientating frameworks". Similarly, in their 1995 review article, Garnett *et al*. advocated having a list of "conceptual and propositional knowledge" (p 83) as a starting point for further research into misconceptions. Describing student conceptual difficulties as *Limited or Inappropriate Propositional Hierarchy* (*LIPH*), as suggested by Novak and Gowan (1984), shows that these propositional statements are essential; how else does a researcher adjudicate what is missing or inappropriate? I anticipated needing such a set of propositional knowledge when formulating Research sub-questions 2c, 3c and 4c. Treagust (1988; 1995) outlines a method for deriving a coherent set of propositional statements from expert knowledge. A further aspect of Treagust's method includes developing concept maps to establish coherency or internal validity of propositions within a topic. Both aspects are important pedagogic knowledge for teachers in a discipline.

2.5 A SUITABLE TOPIC FOR REVIEW

2.5.1 The Importance of acid-base chemistry

Acid-base chemistry is an important topic in a chemistry curriculum. The topic has been described by chemistry education researchers as "fundamental" (Morgil *et al*., 2005), one of the "big ideas" in chemistry (Chiu, 2007) and "relevant" for medical students (Tarr & Norwell, 1985) and is also ranked by teachers as among the fifteen most important topics in chemistry (Finley e*t al.*, 1982). In addition, through studying acid-base chemistry, students learn about both the nature of scientific models and many everyday processes (Drechsler & Schmidt, 2005a), as well as processes applied in other sciences. In this regard, Oversby (2000a) highlights the pervasiveness of acid-base chemistry in other topics such as the nature of inorganic oxides of metals and non-metals, or the acidity of phenols and carboxylic acids in organic chemistry. Furthermore, introductory college biology may include acid-base chemistry in cellular processes, such as protein and nucleic acid denaturising, enzyme activity, oxygen and carbon dioxide transport (Rhodes, 2006; Watters & Watters, 2006). Despite this stated importance, recent general reviews report very few student difficulties in the topic of acid-base chemistry; for example, Kind (2004) reported five, contrasting with 20 reported for each of electrochemistry and particulate nature of matter, while Garnett *et al.* (1995) reported nothing specifically on the chemistry of acids and bases. Currently, the literature contains no specific review on the topic of acid-base chemistry.

2.5.2 The potential of acid-base chemistry for misconceptions and difficulties

It could be argued that acid-base chemistry does not yield many difficulties, but this is hardly true in light of teachers', students' and educationists' ideas of the complexity of acid-base chemistry as follows. In the United Kingdom, senior chemistry teachers rated the topic as the third most difficult to teach (Ratcliffe, 2002). Among Swedish chemistry teachers, none rated the topic as their favourite; they anticipated mostly mathematical rather than conceptual difficulties (Drechsler & Schmidt, 2005a). Some students also dislike the topic. Specifically, Tarr and Norwell (1985) describe feelings of fear, hopelessness and intolerance among medical students who often resorted to rote and algorithmic learning: "Nothing, it seems, is as universally misunderstood and difficult to convey as the concepts surrounding the biological responses to hydrogen ions" (p 14). New Zealand secondary school students thought acid-base chemistry was a difficult topic, especially where ionic equations are needed. They rated their performance as third poorest in 50 topics (Burns, 1982). Similarly, Wisconsin students ranked pH as the fifth most difficult topic in chemistry (Finley *et al.*, 1982). Ratcliffe's (2002) report suggested that students held very different views to their teachers (above). These students thought there were 15 other chemistry topics more difficult to learn than acids and bases. In the same vein, Furió-Más *et al.* (2005) noted Spanish students' belief that it was a simple topic, even boring. Swedish teachers, mentioned above, also thought it was superficial, offering little further extension beyond students' experience in junior secondary school (Drechsler & Schmidt, 2005a). However, as noted earlier (see Section 2.4.4), teachers tend to underestimate the impact of student conceptual difficulties (Agung & Schwartz, 2007). In summary, the topic is recognised as being important, but teachers appear to dislike the topic but for different reasons, seeing it either as undemanding or presenting mostly mathematical difficulties. Students' opinions vary; some rank its difficulty level high and others low.

Adding to the surveys above, research suggests that the high cognitive demands associated with studying acid-base chemistry will probably yield conceptual difficulties. To be specific, Herron (1975) anticipated that students who do not reason abstractly would struggle to "conceive an acid as a proton donor or electron pair acceptor" although they should not have trouble conceiving "an acid as any substance that will turn litmus red". This reflects Johnstone's (e.g. 2002) contention that many difficulties in learning chemistry arise from different representations in chemistry; specifically the macroscopic, molecular and symbolic. Furthermore, acid-base chemistry involves several distinct models (e.g. Kolb, 1978, Oversby, 2000a) and student difficulties in such situations have been recorded (e.g. Justi & Gilbert, 1999). Specifically, according to Nakhleh and Krajcik (1994), the topic requires a deep understanding of atoms, molecules, ions and chemical reactions, and on a similar note, Johnstone (2002, p 13) contends: "Many of the wrong ideas that students have start with ions and salts." It follows that experts in chemistry education research anticipate students having difficulties in the acid-base topic.

Different categories of concepts might be assimilated in differing ways according to a student cognitive level. In this regard, Wilson (1998) found that weaker students tended to use matter concepts (such as acid or base) around which to organise their knowledge, while more advanced students were able to use process concepts (such as ionization) for the nodes in their concept maps. As a result, she suggests that teachers use the first, more concrete, category as an organisational framework for novice learners; the second, more abstract, category being more suitable for advanced students. This aspect suggested there could be different categories of difficulties according to the central organising idea – namely chemical species or processes. Furthermore many reports concerning student difficulties in interpreting representations used in chemistry, such as scientific terms (see Section 2.3.2), mathematical expressions (e.g. Potgieter *et al*., 2008) or chemical symbols (e.g. Yarroch, 1985; Treagust & Mamiala, 2003) suggest that difficulties with representations can be expected to pervade all aspects of chemistry.

2.5.3 Acid-base presentation in textbooks.

Textbook inaccuracies with acid-base chemistry have also been reported (e.g. Carr, 1984). Specifically, Loeffler (1989, p 929) pointed out: "the entire field of acid/base chemistry is filled with ambiguous or seemingly inappropriate word usage and symbolism". Recent content analyses of the acid-base topic carried out on textbooks published in the United Sates (Erduran, 1996; de Vos & Pilot, 2001), the United Kingdom (Oversby, 2000a), Spain (Furió-Más *et al.*, 2005), Greece (Kousathana *et al.*, 2005) and Sweden (Drechsler & Schmidt, 2005a; Drechsler & van Driel, in press) indicate a persistent and widespread problem. All these studies report instances of hybrid or mixed acid-base models and corresponding lack of distinction between applicable contexts for the models, resulting in an incoherent presentation for readers. Moreover, textbooks are sometimes contradictory; to be specific, different definitions of acids are given almost contiguously without differentiating contexts (Evans & Lewis, 1998), while textbook explanations of relative strength of acids in water have been described as "nebulous" and sometimes inconsistent with explanations, such as strength of chemical bonds given later in a book (Moran, 2006, p 800). Formal instruction has already been implicated in student conceptual difficulties (see Section 2.3.4) and, clearly, textbooks could be an important cause of student conceptual difficulties in this area of chemistry. Accordingly, a need for a different source of propositional knowledge in the topic was anticipated in the current research.

2.6 CONCLUSION

This review has shown that learning science and, in particular, chemistry is no easy matter. Students need to form appropriate links between concepts but sometimes difficulties may occur because students filter and interpret new information, so making their own idiosyncratic conceptions. If these conceptions are not in accordance with accepted scientific knowledge, they indicate a limited or inappropriate propositional hierarchy (LIPH) which may also be termed a misconception, or alternative conception or simply a conceptual difficulty. Causes may lie within the nature of science in general, and chemistry (with its large abstract component and multi-representational nature) in particular, or have pedagogic origins.

Research into student conceptions has so far had little influence on the efficacy of science instruction. A possible reason is a dearth of reviews and syntheses of isolated research studies. Acid-base chemistry is an important topic in itself as well as a foundation for allied sciences and since it encompasses several models, which are sometimes misrepresented in textbooks; it could be a fruitful field for misconceptions, which may fall into categories of species, processes and representations. Consequently, a comprehensive analysis of student difficulties in acid-base chemistry should be useful for practitioners and help facilitate effective teaching. In addition, corresponding propositional knowledge, which appears lacking or inappropriate among students, needs to be presented in a manner that is both useful for textbook authors and enhances teachers' PCK. Thus the goals of the present study have been to critically analyse research done to identify conceptual difficulties in acid-base chemistry through an approach which matches such difficulties specifically to sound propositional knowledge. This could, *inter alia*, be used to improve textbook descriptions of acid-base concepts, help develop practitioners' PCK and facilitate remediation of any student difficulties. Towards this goal I addressed the research questions already presented in the Introduction (Chapter 1) which, for readers' convenience are given again below.

Research questions addressed in this study

1) *What is the nature of research published on student difficulties with acid-base chemistry?*
    a) *Which reports give suitable research data on student conceptual difficulties in acid-base chemistry?*
    b) *What is the scope of this research?*
    c) *What is the overall quality of this research?*
2) *What difficulties do students experience with species in acid-base chemistry?*
    a) *What descriptions of difficulties with acid-base species can be synthesised from existing research data?*
    b) *How stable are these difficulty descriptions across different contexts?*
    c) *What statements of propositional knowledge are needed to address difficulties with species in acid-base chemistry?*
3) *What difficulties do students experience with acid-base properties?*
    a) *What descriptions of difficulties with acid-base properties can be synthesised from existing research data?*
    b) *How stable are these difficulty descriptions across different contexts?*
    c) *What statements of propositional knowledge are needed to address difficulties with acid-base properties?*
4) *What difficulties do students experience with terminology and symbolism in acid-base chemistry?*
    a) *What descriptions of difficulties with acid-base terminology and symbolism can be synthesised from existing research data?*
    b) *How stable are these difficulty descriptions across different contexts?*
    c) *What statements of propositional knowledge are needed to address difficulties with acid-base terminology and symbolism?*

5) *Does the set of propositional knowledge statements derived through analysis of student difficulties reflect appropriate knowledge for teaching and learning acid-base models?*
    a) *How well do the propositional statements reflect curriculum models for acid-base chemistry?*
    b) *What are the implications of the propositional knowledge for teaching and learning acid-base chemistry?*

CHAPTER 3

THEORETICAL FRAMEWORK AND CONTEXT OF THE STUDY

3.1 INTRODUCTION – THE NATURALISTIC PARADIGM

A research paradigm can imply the set of symbolic generalizations, models, values and exemplars that are shared as a “disciplinary matrix” by members of a given community (Kuhn, 1970, pp 174-187). Lincoln and Guba (1985, p 15) clarify that a paradigm entails “a systematic set of beliefs together with their accompanying methods” which they emphasise should be enabling rather than constraining. These authors give multiple constructed realities as one axiom of a paradigm for naturalistic enquiry. The notion of multiple realities is inherent in an idea of students’ differing conceptions. Therefore, the present research study is framed within naturalistic enquiry in order to evaluate existing research already carried out on student difficulties in acid-base chemistry. Some implications arising from the axioms of naturalistic enquiry given by Lincoln and Guba (1985, p 39) include observations being context dependent, and the relevance of purposive sampling. These aspects informed Research question 1 and the means used to address it. In this matter, firstly, a search for publications should be purposive (Research question 1b). Then the scope and quality of published research should be investigated in order to understand the context of each investigation (Research sub-questions 1b and c), before research outcomes from those publications could be analysed. This evaluation then feeds into Research questions 2, 3 and 4 which involve determining what difficulties can be described concerning conceptual difficulties among students. Qualitative analysis also achieves “some level of understanding” (Lincoln & Guba, 1985 p 37) and the level of understanding reflected in difficulty descriptions will be considered in Research sub-questions 2b, 3b and 4b.

A notion of comparing student conceptions to propositional knowledge accepted by a scientific community falls within a nomothetic or science-centred paradigm (Wandersee *et al*., 1994). However, Lincoln and Guba (1985) suggest that, instead of looking for separate cause and effect, naturalistic enquiry is a holistic enquiry, thereby allowing parts to work synergistically together, mutually shaping each other. Consequently, Research sub-questions 2a, 3a and 4a (descriptions of student difficulties) would be investigated alongside Research sub-questions 2c, 3c and 4c (propositional knowledge statements). In other words, propositional knowledge statements would be formulated according to particular student difficulties that were identified rather than as a starting point.

Anticipating mostly qualitative data published as student conceptions, Maxwell’s (2005) recommendation for a conceptual framework was adopted. He suggests that “the system of concepts, assumptions, expectations, beliefs, and theories that supports and informs your research” (p 33) could be considered as a model of what is happening in a research problem. Its function is to guide and frame a research design as to its goals, research questions, methods and validity threats. Components of this framework include prior theory and research, together with experiential knowledge of the researcher. Accordingly, these follow next.

3.2 SCIENCE EDUCATION CONTEXT

Osborne (1996) asserts that the most valuable outcome of a research paradigm of constructivism has been to show up the extent of difficulties which students have with learning, and applying appropriately, explanatory models of science.

3.2.1 Constructing science knowledge

Knowledge is an active human construction. Knowledge is not passively received (von Glasersfeld, 1995a) nor is it merely “discovered like gold” but rather it is “constructed like pyramids or cars” (Novak & Gowan, 1984, p4). Being organised and with potential for application, knowledge goes beyond mere information. This ability to make meaning of the world is uniquely human (Mintzes & Novak, 2000). It follows that knowledge is not inherently out there waiting to be unearthed or passed on; instead humans actively build it up.

Knowledge is also personally constructed; individuals do not simply mirror and reflect what they receive. According to von Glasersfeld (1995a; 1995b), reality cannot be accessed directly, so individuals simply construct a view of reality based on personal observations and experiences. A person will retain the set of ideas and actions that are both “viable” and useful – knowledge is good if it works for an individual. Similarly, Duit and Treagust (1995) view learners as sense makers, so constructed knowledge should fit one’s personal understanding of the world. Therefore, as learners construct their own meanings of words, visual images or other stimuli, they are personally selecting, interpreting and ordering information according to prior conceptions while ignoring contra-examples. Because of this filter, it is impossible to transfer ideas intact from teacher to learner as “nuggets of truth” (p 49). This aspect of constructivism infers that students will form diverse conceptions, despite all receiving similar teaching.

Knowledge is also socially mediated as it is embedded within an individual’s social setting, including personal history and cultural background. Radical constructivism is not concerned with whether personal knowledge is accepted by consensus, but simply that it works for a person (von Glasersfeld, 1995a; 1995b). By contrast, human or social constructivists emphasise an individual’s context or personal frame of reference when making sense of new material; so knowledge is mediated by social interaction (Duit & Treagust, 1995). The culture of science involves ideas, initially constructed by individuals through interaction with natural phenomena and then scrutinized before acceptance by peers (Driver, 1995; Osborne, 1996). Thus, despite being widely held, not all cultural ideas (for example UFO’s) are given equal weight by a scientific community (Mintzes & Novak, 2000). Progress of ‘normal science’ requires that novices be acculturated into the unequivocal tradition of a particular field (Kuhn, 1970). Therefore the culture of science, into which students will be inducted, includes a body of knowledge that has been judged credible by a scientific community. These consensually held ideas, rather than personal theories about phenomena, are, according to Millar (1989), the core of science teaching. This idea informs the need to have propositional knowledge statements against which descriptions of student conceptions may be compared. Moreover, these statements should reflect consensual expert knowledge in the discipline.

From these two arguments, there appears to be a dichotomy between personal construction of knowledge and consensual social construction of scientific knowledge. While there is considerable support for a teacher’s role in social mediation of scientific knowledge (e.g. Hodson, 1992; Treagust *et al,* 1996a; Mintzes *et al*., 2000), Matthews (1994) believes that teaching which involves transmission of a body of knowledge is better termed good education rather than constructivism. However, Solomon (1994) distinguishes between learners having their own theories about reality, which make sense to them, and established scientific theories that formal instruction should enable them to recognize. She contends: “Constructivism ... has always skirted around the actual learning of an established body of knowledge” (p16). Similarly distinguishing these two aspects, Osborne (1996) argues that construction of new knowledge is an epistemological issue, whereas learning existing constructs of that knowledge is an educational issue. They are not the same, nor does one necessarily govern the other. He continues: “...the advocates of constructivist methods of teaching have failed to recognize that there is a role for telling, showing, and demonstrating …it is false to assume that a belief in constructivism implies that all knowledge must be negotiated” (p 67). Accordingly, learning what is already known in science, whether by direct experience or through explicit instruction, should be meaningful, as expounded by human constructivists. It then follows that comparing students' individually constructed, and possibly diverse, ideas with a norm of scientifically accepted knowledge will be necessary for this research project to have outcomes acceptable within a community of scientists, chemists in particular. Scientifically accepted knowledge implicated in the difficulties (from Research sub-questions 2c, 3c and 4c) can then become a focus for developing more effective teaching (Research question 5).

3.2.2 Meaningful Learning

Meaningful learning concerns the way in which an individual actively absorbs new knowledge rather than the manner in which knowledge is received, so it includes both well-designed reception learning and discovery learning. Meaningful learning requires that individuals choose to relate new knowledge to prior knowledge in a non-arbitrary way. This coherence will show in their being able to use it appropriately. Construction of a framework of relationships is what makes learning meaningful (Mintzes & Wandersee, 1998). When learning meaningfully, a learner activates existing knowledge and relates it to new experience. This newly constructed knowledge may then be applied, evaluated and possibly revised (Glynn & Duit, 1995). Meaningful learning goes beyond memory tricks and super-learning strategies (Novak & Gowan, 1984), beyond a "facade of stored factual knowledge" (Duit & Treagust, 1995, p 46) or "knowledge in pieces" (diSessa, 1998). Meaningful learning implies understanding (West & Pines, 1985) and therefore can include receiving and integrating an established body of knowledge. To learn meaningfully is to understand.

Understanding involves the extent, connectedness and utility of knowledge. It is dynamic rather than a dichotomous state; it improves as the amount of knowledge increases and elements become more intensively linked (White & Gunstone, 1992; Mintez & Novak, 2000). For example scientific facts and formulae should be set within the fundamental qualitative ideas from which they are derived (Larkin & Reif, 1976; Duit & Treagust, 1995) – this is transparency – without being encumbered with unnecessary detail (Mintzes & Novak, 2000). Connections will be logical (that is coherent) but also particular, according to a learner's own prior knowledge and beliefs (Smith, 1991; Mintez & Novak, 2000). Usefulness entails being able to apply knowledge in new situations (Duit & Treagust, 1995) or perform socially worthwhile tasks in an appropriate manner (Smith, 1991). A consensually recognized referent group should share the constructed meanings (Mintez & Novak, 2000). Thus, understanding enables an individual to participate meaningfully in a community of practitioners, such as scientists, due to a rich, well-connected and internally consistent network of knowledge. In answering Research question 5, the propositional knowledge statements will be evaluated against criteria which reflect these aspects of ‘understanding’, namely consensus, consistency, parsimony (or brevity) and transparency.

3.2.3 Propositional knowledge

Propositions are part of well-connected knowledge as described in the previous section because they represent discrete relationships linking two concepts (Novak & Gowan, 1984; Novak, 2002). A proposition is not in the words themselves but in their meaning (Sutherland, 1989; Pinto & Blair, 1993; Colman, 2001). One may also make an implicit proposition – expecting an audience to go beyond explicit statements and draw conclusions (Pinto & Blair, 1993). As discrete units, propositions can be judged true or false, truth depending on “shared values” or context of propositions (Lincoln & Guba, 1985, p 31).

Propositions link concepts in a hierarchical fashion, and Novak and Gowan’s (1984) idea of a limited or inappropriate propositional hierarchy or LIPH (see Section 2.2) indicates that conceptual difficulties arise when students have an inappropriate link or an important link missing in their conception of a concept. Accordingly, identifying which propositional link is troublesome is implicit in determining the nature of their conceptual difficulty, and so being able to describe it. This indicates that it would be practical to investigate these two aspects at the same time; that is, answers could be sought for Research sub-questions 2a and 2c, 3a and 3c and 4a and 4c simultaneously, in accordance with the holistic nature of naturalistic enquiry (Lincoln & Guba, 1985, see Section 3.1).

3.2.4 Models

Learning *about* science (that is, understanding what is involved in the conduct of science) is considered to be one of three main purposes of science education (Hodson, 1992). According to Lakatos (1978), each historical programme in science has a *hard core* which is its theoretical context – the consistent main ideas (or models) and analytical tools on which it is based – and a p*rotective belt* which is an auxiliary theory that is more flexible and used to defend the hard core in explaining phenomena. Taber (2001a) argues that theoretical chemistry is largely comprised of models so that student difficulties in chemistry tend to be epistemological (where students think that models are reality) or pedagogical (caused by instruction) rather than ontological; in other words, they do not generally involve naïve conceptions as typically found in physics. This echoes Carr (1984, p 97) who observed that student difficulties are "more usually perceived in terms of confusion about models used in teaching the concept than as a conflict between preconceptions and the scientific view".

Experts choose an appropriate model for a particular purpose, from knowledge of strengths and limitations of particular models, rather than from a particular hierarchy (Oversby, 2000a). The very nature of a model is to provide a simplified representation of a target (an object or process) (Glynn *et al*., 1991) so it is customary to deliberately exclude some aspects of the target (Drechsler & Schmidt, 2005a). In this way a certain context may lend itself to a simpler historical model, despite this model not being currently a focus of research. It follows that models learned earlier retain their usefulness but more advanced students might be expected to have a greater variety of models at their disposal. A later model does not necessarily replace an earlier one. A chemistry curriculum, therefore, needs to expose students to a variety of models and also to present historical models with their hard core intact. This could help address two aspects: the epistemological nature of science (science knowledge is tentative and evolving) and also show the relevance of different models for different contexts; with appropriate scientific conceptions and reasoning applicable within each model. These aspects have informed the nature of propositional knowledge to be derived through Research sub-question 2c, 3c and 4c and evaluated in Research question 5. Each acid-base model needs to be carefully defined and differentiated.

Justi and Gilbert (1999) identified the hard cores in different historical models of reaction kinetics using original research papers as well as history of science publications. They analysed these in terms of:

1. Deficiencies in explanatory capability of previous models,
2. Features of former models that have been modified and incorporated into new model,
3. How the new model overcomes and explains deficiencies of previous models,
4. Unanticipated explanatory benefits of the new model,
5. Explanatory deficiencies of the new model.

These aspects will be used to maintain the integrity in the hard-core of each model as described by propositional knowledge statements.

3.2.5 Expert – Novice Knowledge

Leaning is about making connections (see Section 3.2.2). Both experts creating new knowledge and novices learning existing knowledge must make connections between prior and new conceptions (Mintzes & Wandersee, 1998a). However, novices frequently do not make connections and new knowledge might remain disconnected. Isolated pieces of understanding, or p-prims, are accessed in different contexts, (diSessa, 1998). Because novices do not appreciate inconsistencies or gaps in their knowledge structure, they struggle to make meaning of their new knowledge, so they have little understanding. By contrast, the chief product of meaning making is a well-integrated, highly cohesive knowledge structure (Mintzes & Wandersee, 1998) as reflected in a concept map of propositional statements. The concept maps used in this dissertation will be evaluated under Research question 5.

Connections in an expert's knowledge structure may well be tacit. According to Frappaolo (2006), tacit knowledge is personal, embedded in experience, and forever changing, growing and being reshaped. Because it is based in a community of practice, coding tacit knowledge into an explicit communicable form is a challenge. This coding process involves capturing elusive aspects such as thought processes; that is, the "logical, methodological thinking processes that are simply not recognised as such, even by the thinker" (Frappaolo, 2006, p 12). These subtle interrelations (Lincoln & Guba, 1985) enable experts with greater tacit knowledge to choose appropriate procedures for different problems. In the chemistry context experts' tacit knowledge includes knowing which model to use in a particular context and knowing particular meanings for words and symbols in these contexts. This is the knowledge that needs to be coded and compared with that of students. The acid-base context is where it will be applied.

3.3 CHEMISTRY CONTEXT

Experts in chemical education believe that their field constitutes a branch of chemistry. Bunce and Robinson (1997) substantiate this view by drawing analogies with research into natural products or analytical chemistry. However, they argue that if science education researchers wish to be considered representatives of a community of chemists, researchers need to have a detailed knowledge of the chemistry concerned. Moreover, because it is the actual chemistry content that causes difficulties for students, researchers need to make explicit the chemistry background in question (Eybe & Schmidt, 2001).

Numerous publications distinguish acid-base models for chemistry educators (e.g. Kolb, 1978; Rayner-Canham, 1994; Oversby, 2000a; de Vos & Pilot, 2001). These include an operational or behaviour model used from antiquity together with theoretical models put forward by Lavoisier, Arrhenius, Brønsted and Lewis. The Lavoisier model – "acids are substances that contain oxygen" – may be considered obsolete and is usually included in high school curricula while the Lewis model is usually included only in tertiary studies (Oversby, 2000a). Accordingly, my analysis of student difficulties has not included either of these models. The core aspects of three models (Operational, Arrhenius and Brønsted) are summarised next, followed by brief details of the Lewis model which influenced interpretation of some data. Lastly, an outline of the pH concept, which pervades all the models, is given. In this section, a number of chemical equations are introduced that will be referred to later when interpreting data. These are summarised at the end of the section. Strictly speaking, species in aqueous medium should be indicated thus: $H_3O^+(aq)$ but for simplicity necessary for novice students, in many instances the (aq) subscript has been omitted.

3.3.1 An Operational Model

An operational model has been used from antiquity to describe acids and bases (sometimes called alkalis) in terms of macroscopic properties displayed. Operational definitions to show how a property might be recognised or measured remain relevant today (Galili &Lehavi, 2006). In this operational context substances or their solutions were hardly distinguished (de Vos & Pilot, 2001); for example, does a bottle labelled *sulfuric acid* indicate pure 'oil of vitriol', or a diluted aqueous solution? It is acidic and basic substances which tend to neutralize each other; the products are a salt and water. Priestley's model (acids are substances that contain hydrogen) allows use of formulae to show substances in an acid-base reaction (Oversby, 2000a) in the form of: acid + base ⟶ salt + water

A typical example for this scheme could be: $HCl + NaOH \longrightarrow NaCl + H_2O$

Such an equation remains useful in quantitative analysis of an acid or a base by means of a titration. This model is predictive and offers no reason for the reaction to take place.

3.3.2 The Arrhenius Model

In the 19th century, Arrhenius suggested in his PhD thesis that ions formed when salts dissolved in water rather than, as previously believed, only once a current was passed through the solution (Kolb, 1978). From this proposal, a new explanatory paradigm arose, wherein acids or bases were substances, which dissociated in aqueous solution to produce hydrogen (H^+) and hydroxide (OH^-) ions respectively (for example Arrhenius, 1903; 1912). In this model, the particular acid or base is considered irrelevant as all neutralization reactions are fundamentally the same; hydrogen ions from the acid react with hydroxide ions from the base and the primary product is water. It follows that the Arrhenius model does not consider formation of a specific salt, although one could be isolated by evaporation of the resultant solution. An ionic equation may be used to represent the reaction, in either a complete or net ionic form (Drechsler & Schmidt, 2005a).

$$(H^+ + Cl^-) + (Na^+ + OH^-) \rightarrow (Na^+ + Cl^-) + H_2O \qquad \text{or} \qquad H^+ + OH^- \rightarrow H_2O$$

Equations with single arrows as shown above would indicate the reaction goes to completion. In this model, water molecules dissociate partially, so the equation below shows the reversibility of the equilibrium system: $H_2O \rightleftharpoons H^+ + OH^-$

The ion-product constant for water is given by: $K_W = [H^+][OH^-]$ where square brackets [ ], represent concentration of the indicated species, in this case at equilibrium. This infers that in an equilibrium system a higher concentration of hydrogen ion infers a lower concentration of hydroxide ions, and vice versa.

3.3.2.1 Acid-base strength in the Arrhenius model

Being based on electrolytic theory, the Arrhenius model treats acids and bases as electrolytes; those that are fully dissociated into ions are strong, while those that are not fully dissociated are weak. Typical equations representing the dissociation process for strong acids and bases are:

$$HCl \rightarrow H^+ + Cl^- \quad \text{and} \quad NaOH \rightarrow Na^+ + OH^-$$

Concentrations may be obtained from electrical conductivity of solutions, to give values for corresponding equilibrium constants K_a and K_b, also known as dissociation constants.

$$K_{a\,HCl} = \frac{[H^+].[Cl^-]}{[HCl]} \quad \text{and} \quad K_{b\,NaOH} = \frac{[Na^+].[OH^-]}{[NaOH]}$$

The model is limited to aqueous solutions, so differences in strength between acids and bases that are 100% dissociated will not be detected. Dissociation of a weak acid could be represented as a reversible system such as:

$$CH_3COOH \rightleftharpoons CH_3COO^- + H^+$$

The corresponding dissociation constant for the equilibrium is

$$K_{a\,CH_3COOH} = \frac{[H^+].[CH_3COO^-]}{[CH_3COOH]}$$

K_a for HCl will be much greater for than for CH_3COOH (Bell, 1969, pp 13, 16). Consequently, for the same bulk concentration of monoprotic acids, such as HCl and CH_3COOH, the solution of a stronger acid will have a higher concentration of ions.

Polyprotic acids dissociate in two or more stages, thus for diprotic sulfuric acid:

$$H_2SO_4 \rightleftharpoons HSO_4^- + H^+ \quad \text{and} \quad HSO_4^- \rightleftharpoons SO_4^{2-} + H^+$$

Consequently, a polyprotic acid may have a higher concentration of hydrogen ions than monoprotic acids of similar strength.

3.3.2.2 Aspects of the protective belt for the Arrhenius model

Some ways in which challenges from empirical observations have been accommodated by adjusting the protective belt of the Arrhenius model are discussed next. The Arrhenius model accommodates the first challenge presented by the basic nature of a solution of ammonia (NH_3) which has no hydroxide group, through postulating formation of molecular ammonium hydroxide, which could dissociate partially in solution (e.g. Kobe & Markov, 1941; Tuttle, 1991), thus: $NH_4OH \rightleftharpoons NH_4^+ + OH^-$

However, modern chemists have challenged the existence of ammonium hydroxide (e.g. Laing & Laing, 1988; Yoke, 1989). In particular, Davis (1953) maintains: “Nothing is gained in clarity or understanding by continuing the fiction of the reality of the ammonium hydroxide molecule”.

A further challenge to the Arrhenius model arises concerning the phenomenon of substances that do not themselves dissociate into hydrogen or hydroxide ions (so not fitting definitions of acids or bases) but still have acidic or basic aqueous solutions (Rayner-Canham, 1994). In each case the salt is first presumed to dissociate – which in itself may not be completely true (Hawkes, 1996a). The acidic nature of an ammonium chloride solution may be explained by production of excess hydrogen ions depicted as follows:

$NH_4Cl(s) \rightarrow NH_4^+(aq) + Cl^-(aq)$ followed by $NH_4^+(aq) \rightleftharpoons NH_3(aq) + H^+(aq)$

To explain these empirical observations concerning salts such as sodium ethanoate (acetate) or sodium carbonate, which have basic aqueous solutions, Arrhenius acid-base theory includes a notion of these ionic species being hydrolysed, or reacting with water, whereby ions from weak acids produce the original weak acid (un-dissociated) and excess hydroxide ions. For sodium ethanoate, excess hydroxide ions can be produced according to the equations:

$$CH_3COONa(s) \rightarrow CH_3COO^-(aq) + Na^+(aq) \quad \text{and}$$

$$CH_3COO^-(aq) + H_2O(l) \rightleftharpoons CH_3COOH + OH^-(aq)$$

A similar process is shown by the following equations for sodium carbonate:

$Na_2CO_3(s) \longrightarrow 2Na^+(aq) + CO_3^{2-}(aq)$ and $CO_3^{2-}(aq) + 2H_2O(l) \rightleftharpoons H_2CO_3(aq) + 2OH^-(aq)$

As the equations above show, the aspect of the protective belt needed to explain the phenomenon of acidic or basic solutions also relies on the existence of carbonic acid (H_2CO_3) which is again merely postulated. The phenomenon of basic solutions for salts is also explained much more simply by the Brønsted model, as will be shown below.

3.3.2.3 Terminology: dissociation and ionization in the Arrhenius model.

The terms ionization and dissociation appear to have been used interchangeably to indicate the process whereby electrolytes provide ions in solution. For example "According to this theory strong acids and bases, as well as salts, are in extreme dilution completely dissociated" Arrhenius, 1903, p51) and "ionization of sodium chloride..." (Arrhenius, 1912). Even with modern knowledge of bonding, de Vos and Pilot (2001) use ionization in relation to acids and bases in solution. For clarity I have used dissociation for all these processes concerning the Arrhenius model.

3.3.3 The Brønsted Model

A paradigm shift arose from work by Lowry (1923a) and Brønsted (for example 1923; 1926). Brønsted developed this new model further and so it is frequently referred to simply as the Brønsted model. It is based on the reaction scheme: an acid is a proton donor while a base is a proton acceptor, the process represented as: $\text{acid} \longrightarrow \text{base} + H^+$

The model differs from earlier models in important ways.

- It does not classify substances, but rather molecular or ionic species.
- There is no absolute classification; instead behaviour of species in a given reaction determines their classification.
- Acid and base are present, both as reactants and products: acid_1 forms conjugate base_1, while base_2 forms conjugate acid_2, as shown by a general reaction scheme
  $\text{acid}_1 + \text{base}_2 \rightleftharpoons \text{acid}_2 + \text{base}_1$
- The model is not limited to aqueous solutions.
- The model is not limited to neutralization reactions.
- Bases are not limited to those with a hydroxyl group, OH, so molecules such as ammonia (NH_3) and amines are easily accommodated as weak bases.

These differences are explained next.

3.3.3.1 Acid-base species are particles in the Brønsted model

Most fundamentally, the model focuses on molecular or ionic species behaving as acids and bases rather than classifying macroscopic substances, although this was not explicit in early publications; for instance, Lowry (1924, p 1021) states: "An acid may be defined as a hydride from which a proton can be detached" and Brønsted (1926, p 777) writes: "An acid is a *substance* able to split off H^+ ions simultaneously forming a base" (my italics). However, later on the same page, Brønsted clarifies that his scheme "involves the admittance of the acid and base properties being in principle assignable to ions as well as neutral molecules". In a later publication, this is clarified by: "An acid is a *molecule* with a tendency to split off a hydrogen nucleus" (my italics) and a few sentences later: "some of the molecules are neutral and others electrically charged" (Brønsted & Guggenheim, 1927, p 2554). Clearly, Brønsted had particles rather than substances in mind. Accordingly, they should be referred to as species rather than substances (Loeffler, 1989). Furthermore, although Kolb (1978, p462) asserts that Brønsted had "significantly broadened the definition of the word *base*...", many common Arrhenius bases such as NaOH cannot be placed directly into the Brønsted reaction scheme. For instance examples of (electrically) neutral bases include NH_3 (Brønsted, 1923; Kolb, 1978) and H_2O (Kolb, 1978), whereas, neither author mentions NaOH or KOH. Furthermore, Lowry (1923, p46) explains "The hydroxyl ion is itself a strong base, since it is capable of accepting the ... hydrogen ions." If NaOH was a Brønsted base, it would have a conjugate acid but Brønsted (1926) noted that sodium ions in aqueous solution demonstrated no acidic properties, unlike magnesium and aluminium ions. Moreover, in the latter cases, he explains that it is the hydrated cation which is capable of donating a proton, so acting as an acid. Consequently, for metal hydroxides such as NaOH or KOH, *base* no longer refers to the substance, or even the simple ionic formula unit, but rather the hydroxide ions produced on dissolution (Lowry,1923). Relating the Brønsted model to such substances, or their chemical formula, is an example of a hybrid model (de Vos & Pilot, 2001). In addition, because the term *alkali* relates to substances it has no place in the Brønsted model (Schmidt & Volke, 2003).

The IUPAC definitions for modern chemists promote an authentic model. A Brønsted acid is "a molecular entity or chemical species capable of donating a hydron". Similarly, a Brønsted base is "a molecular entity capable of accepting a hydron" (McNaught & Wilkinson, 1997). Nevertheless, a hybrid model persists in some definitions of an acid even in modern chemistry handbooks, as shown by Lide (2002) "In the Brønsted definition, an acid is a *substance* that donates a proton in any type of reaction ... a base is a *substance* capable of accepting a proton in any type of reaction" (my italics). The term 'hydron' used in IUPAC definitions indicates all hydrogen isotopes, represented as H^+ (McNaught & Wilkinson, 1997). However, this term has not been generally accepted in text books – even at tertiary level – (pers.com Southway) so in the current work I have retained the word 'proton'.

3.3.3.2 Neutralization in the Brønsted model

Because a Brønsted scheme includes non-aqueous systems, water is not necessarily a product and, again, salts have no place in this reaction scheme. Moreover, in 1923, Brønsted clarified: "The hydroxyl ion in principle has no special position as a bearer of basic properties." Indeed, neutralization is not unique; rather it is but one of many acid-base reactions, as Schmidt (1995) clarifies: "The term neutralization (in its original meaning) cannot be applied to acid-base reactions according to Brønsted." Oversby (2000a) explains further: neutralization is a *process* rather than a *point or position*, shown for an aqueous system by the particular ionic equation:

$$H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$$

In this analysis, I use "neutralization" in the Brønsted model to mean the reaction between solvated protons and hydroxyl ions. In this way it is but one of many acid-base reactions alongside hydrolysis or ionization. All of these may or may not proceed to completion according to context. Furthermore, because it does not cover the customary macroscopic acid-base neutralization reaction between substances, this model has limited application in a quantitative analytical context such as titration calculations.

3.3.3.3 Acid-base strength in the Brønsted model

The Brønsted model treats acid-base strength as comparative; there is no dichotomous classification as weak or strong. In this way, some acids or bases are simply stronger or weaker than others, as measured by how readily acids will donate protons or bases will accept protons. Accordingly, many acid-base species can be regarded as amphoteric, because they can behave as either proton donors or acceptors under the influence of other species. Furthermore, because molecules of water (or other solvents) may themselves be proton donors or acceptors, Brønsted (1926) clarifies that comparison of acid-base strength should be made in the same solvent. In aqueous systems, water molecules mask strength differences between two very strong acids or between two very weak acids – termed the 'levelling effect of the solvent'(Kolb, 1978).

3.3.3.4 Terminology: dissociation and ionization in the Brønsted model

In a similar fashion to the Arrhenius model (see Section 3.3.2.3), these two terms are interchanged. Brønsted appears to use dissociation in relation to acids but ionization with respect to bases (e.g. Brønsted, 1926), whereas (Lowry, 1924, p13) clearly differentiates: "... the ionisation of an acid may be, not dissociation as expressed by an equation such as ..., but a double decomposition of the type ...". IUPAC definitions clarify as follows. *Dissociation* is "The separation of a molecular entity into two or more molecular entities" whereas *ionization* is given as "The generation of one or more ions." (McNaught & Wilkinson, 1997). This suggests that ionization creates ions that were not previously there, whereas dissociation merely separates the constituents. Furthermore, in the context of identifying student conceptions, Demerouti *et al*. (2004) and Kousathana *et al*. (2005) distinguish them similarly: *Dissociation* of a substance in water is the phenomenon where ions are released during the dissolution of ionic compounds and *ionization* of a substance in water is the phenomenon where ions are created during the dissolution of molecular compounds. Accordingly, in the interests of distinguishing the interactions which characterise the Brønsted model from the Arrhenius model, I prefer the term ionization to indicate generation of ions which did not previously exist through an interaction between two species or between molecules of the same species as in the self-ionization of water. To illustrate: when acidic or basic substances dissolve in water, acid or base polar molecules interact with polar solvent molecules to form ions according to the model for acid-base reactions shown by ionic equations:

$$HCl + H_2O \rightleftharpoons H_3O^+ + Cl^- \quad \text{or} \quad NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$

HCl molecules will not ionize unless base molecules H_2O are present to accept protons, and similarly, base molecules NH_3 molecules need acid molecules H_2O in order to ionize (Brønsted, 1926). Consequently, the Brønsted model implies that when hydrogen chloride and ammonia dissolve in water, ions are created from molecules; in other words, the substances ionize. When water ionizes, it can be seen as autoprotolysis given by: $H_2O + H_2O \rightleftharpoons OH^- + H_3O^+$

Ionization is a more complex concept than dissociation. It is also more realistic: Hawkes (1992) gives evidence of the energy required to dissociate HCl molecules and likens the idea of this happening of its own accord to donating a purse to a mugger. There need to be two species (acid and base) interacting as in the model for ionization. Indeed, Sacks (2007) promotes the phrase 'proton extractors' to describe Brønsted bases. A further potentially confusing aspect concerns Brønsted acids and bases that are already ions such as NH_4^+ and OH^-, where the notion of how well acids or bases are dissociated is completely inappropriate; acid and base are already single ionic species. Corresponding equilibrium constants (commonly referred to as 'dissociation constants') are given for acid species (Vogel, 1961; Skoog, *et al*., 1996):

$$K_{a\,HCl} = \frac{[H_3O^+].[Cl^-]}{[HCl]} \quad \text{and} \quad K_{a\,NH_4^+} = \frac{[NH_4{}^+].[OH^-]}{[NH_3]}$$

3.3.3.5 Hydrolysis of salts according to the Brønsted model

Acid-base conjugate pairs have reciprocal strengths, so that a weaker acid gives rise to a stronger conjugate base and vice versa. This aspect gives a simple explanation of acidic or basic properties of salts in aqueous solution. Ammonium chloride dissociates into ammonium and chloride ions. Ammonium ions are better hydrogen ion donors than water molecules (that is stronger acids) so the solution will exhibit acidic properties. Correspondingly, sodium ethanoate (acetate) dissociates into ethanoate (acetate) ions and sodium ions. Ethanoate ions are better hydrogen ion acceptors than water molecules (that is stronger bases) so the solution exhibits basic properties.

3.3.3.6 Aspects of the protective belt for the Brønsted model

Acidic behaviour has been shown with aqueous solutions of substances such as aluminium chloride, which have no hydrogen to donate. Brønsted (1926) explains such aspects in terms of hydrated aluminium ions, $[Al(H_2O)_6]^{3+}$, acting as proton donors. These properties are explained more directly with the Lewis model.

3.3.4 The Lewis model

The Lewis model is even more general than the Brønsted model. Furthermore, the focus is on coordinate bond formation rather than species. Acids are electron pair acceptors while bases are electron pair donors as shown by the general scheme below, with: representing an electron pair.

$A + B: \longrightarrow A:B$ Neutralization could be represented as: $H^+ + :OH^- \longrightarrow H:OH$

Unlike the two earlier theoretical models, a scheme according to the Lewis model can explain why reactions occur between polar covalent compounds (Shaffer, 2006). The model is particularly suited to explaining acidic properties of substances without hydrogen atoms which cannot act as proton donors such as anhydrous SO_2 or $AlCl_3$ (Kolb, 1978). Similarly it can explain basic properties of compounds without hydroxide groups, such as amines in organic chemistry (Oversby, 2000a), or anhydrous metal oxides such as calcium oxides as shown below:

$$SiO_2 + CaO \longrightarrow CaSiO_3$$

Some deficiencies of the model include the difficulty in obtaining quantitative data to reflect the differing abilities of species to accept or donate electron pairs, in other words, ranking their strength.

The role of the model in introductory chemistry is contentious. In this regard, Oversby (2000a) considers the acid definition to be so broad that the model loses some explanatory power. In contrast, Shaffer (2006) decries “proton fixation” as found in many textbooks and believes the Lewis model is much more appropriate at introductory university level for understanding why chemical reactions proceed. Sacks (2007) however, contends that Shaffer’s suggested teaching programme obscures the differences between Lewis and Brønsted models, and their relative applicability in different contexts. Customarily, this model is not included in high school curricula (Oversby, 2000a) and for that reason has not been included as a focus of this study but does influence the general context.

3.3.5 A comparison of acid-base models

Table 3.1 below gives a summary comparing acid-base models that will be used to interpret results on student difficulties in chapters 6, 7 and 8. For readers' convenience, they are given as flip-out pages to enable easy cross-reference when reading such discussion. The Lewis model is omitted from this summary as it will not be used in discussion of student difficulties.

Table 3.1 Summary of three acid-base models used in this dissertation

	Operational	**Arrhenius**	**Brønsted**
Taught in	Junior secondary	Junior/ senior secondary	Senior secondary
Context	Predictive reaction between substances, quantitative	Explanatory, classification of substances, quantitative	Explanatory, comparative molecular or ionic behaviour Includes non-aqueous systems
Acid	Characteristic properties e.g. indicators, e.g. HCl, H_2SO_4	Supplier of H^+ ions in water e.g. HCl, H_2SO_4	Proton donor eg HCl, HSO_4^-, NH_4^+
Base	Characteristic properties, e.g. indicators, tends to neutralize acids e.g. NaOH	Supplier of OH^- ions in water. e.g. NaOH, "NH_4OH"	Proton acceptor eg NH_3, OH^-
Acid-base reaction	Neutralization of specific acid by specific base to give specific salt	Neutralization between hydrogen and hydroxide ions	Any proton transfer, e.g. neutralization, ionization, hydrolysis
General equation	Acid + base → salt + water Formulae of substances	$H^+ + OH^- \rightleftharpoons H_2O$ Ionic species	HA + B → BH +A Ionic species
Acid-base strength is...		Degree of dissociation of the substance in aqueous solution	Relative ability to donate or accept protons.
Quantitative strength, acid		$K_a = \frac{[H^+][A^-]}{[HA]}$	$K_a = \frac{[H_3O^+][A^-]}{[HA]}$
Quantitative strength, base		$K_b = \frac{[X^{=}][OH^-]}{[XOH]}$	$K_b = \frac{[HA][OH^-]}{[A^-]} = \frac{K_w}{K_a}$ Where $K_w = [H_3O^+][OH^-]$
Limitations:	Not explanatory	NH_3 is basic Salts can be acidic (NH_4Cl) or basic (Na_2CO_3) Non-aqueous solutions	Acidity of non-protic species, e.g. $AlCl_3$ Stoichiometric quantities of substances, e.g. titrations

The three acid-base models relevant in the current research each has appropriate contexts. Both the operational model and the Arrhenius model focus on substance. The Arrhenius model also considers ionic species formed in solutions, but the Brønsted model considers only species or particles that take part in reactions. In this way it is fundamentally different. Furthermore examples of bases in the Brønsted model do not include any from the earlier models. This model compares relative strength of acids or bases in their ability to donate or accept protons. The constant K_a is very similar in both models, but for Brønsted it always relates to the solvated proton. However, an advantage of Brønsted's model is the relationship between K_a, and the dissociation constant for the solvent, K_w for water, so there is no need for K_b. Each model has its limits, where the model falls down or is inappropriate, usually requiring a later historical model, but sometimes an operational model might remain more appropriate as for stoichiometric calculations. Figure 3.1, which follows, also shows a summary of typical equations used in the three acid-base models.

Operational model, acid-base reaction scheme:	acid + base $\rightarrow$ salt + water	3.1
Operational model example:	$HCl + NaOH \rightarrow NaCl + H_2O$	3.2
Operational model (non-aqueous):	acidic oxide + basic oxide $\rightarrow$ salt	3.3
Arrhenius model, neutralization scheme:	$H^+ + OH^- \rightleftharpoons H_2O$	3.4
Arrhenius example:	$H^+ + Cl^- + Na^+ + OH^- \rightleftharpoons H_2O + Na^+ + Cl^-$	3.5
Arrhenius acid dissociation:	$HA \rightleftharpoons H^+ + A^-$	3.6
Arrhenius base dissociation:	$XOH \rightleftharpoons X^+ + OH^-$	3.7
Brønsted scheme:	acid $\rightarrow$ base + H^+	3.8
Brønsted model, general acid-base reaction:	$\text{acid}_1 + \text{base}_2 \rightleftharpoons \text{acid}_2 + \text{base}_1$	3.9
Brønsted model, neutralization, aqueous:	$H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$	3.10
Brønsted model ionization, acid example:	$HA + H_2O \rightleftharpoons H_3O^+ + A^-$	3.11
Brønsted model ionisation, base example	$H_2O + NH_3 \rightleftharpoons OH^- + NH_4^+$	3.12

Figure 3.1 Summary of acid-base equations used in this dissertation

In an operational model, equations to represent acid-base reactions make use of equations with formulae (equations 3.1, 3.2 & 3.3) for substances, enabling prediction of products (focused on salts) from reactants. This differs from the Arrhenius and Brønsted models which both make use of ionic equations (equation 3.4 to 3.11) in order to explain reactions taking place. Restrictions to neutralization in aqueous solutions are appropriate in Arrhenius acid-base reactions but do not apply in the Brønsted model. Acid-base strength is accommodated in different ways by the Arrhenius and Brønsted models. Degree of dissociation in aqueous solution is used in the Arrhenius model to classify acids and bases as strong (completely dissociated) or weak (degrees of partial dissociation) (equations 3.6 & 3.7). In the Brønsted model, dissociation is an inappropriate term when molecular species are ionized (equation 3.11).

3.3.6 The pH concept

The modern concept of pH for a solution is defined theoretically in terms of activity of hydrogen ions: $\mathrm{pH} = -\log \gamma c_{H^+}$ where γ is the activity coefficient for hydrogen ions in a particular solution, and c_{H^+} is the concentration of hydrogen ions in solution. Activity is influenced by both the solvent and presence of other ions. It is directly proportional to concentration of H^+ in the solution and molecules or ions in solution which are close enough to H^+ ions for their electric fields to interact. It varies slightly with temperature even for a constant hydrogen ion concentration. Activities may cover a large range, from 0.05 to 13, but for seawater it is usually between 0.5 and 0.7. Accuracy of calculations with activities is given as ± 0.02. Where solutions are so dilute and so pure that H^+ ions are not influenced by anything except the solvent, γ tends to 1, so pH = -log c_{H+} or as is often given: pH = -log [H+] (McNaught & Wilkinson, 1997; Lawn, 2003; Hawkes, 1994).

An operational determination of pH may be colourimetrical, such as using ‘Universal indicator’. For this ‘semi-quantitative’ method, accuracy may be as little as ± 1 unit (Lawn, 2003). Modern electrometric analytical methods are reflected in an operational definition from the International Union of Pure and Applied Chemists with a reported accuracy of ± 0.02(McNaught & Wilkinson, 1997), although Lawn (2003) gives slightly greater uncertainty. An electrometric measurement of pH may be used to measure activities, which for all practical purposes may be defined as 10^{-pH} (Hawkes, 1994).

Measurement of pH is usually undertaken between 20°C and 25°C (Lawn, 2003) because pH will decrease as temperature increases. This occurs because of the relationship between hydrogen ion and hydroxide ion concentration which for water is given by the ion product constant $K_w = [H^+].[OH^-]$. Because water dissociation is an endothermic process, increasing temperature will increase K_w; so accordingly, $[H^+]$ also increases. Because of an inverse relationship (see –log above) this will cause a pH decrease with increasing temperature (Skoog *et al.*, 1996). In all these discussions hydrogen ions, given as H^+, refer to solvated ions which in aqueous solution might be represented as H_3O^+ (Lawn, 2003). Measurement of pH relates to a particular effective concentration of hydrogen ions, rather than to a particular substance. Lawn (2003) clarifies this aspect by giving pH values for examples of common household products such as battery acid, shampoo and household ammonia, all of which have particular concentrations. Oversby (2001b) emphasises that: “The concept of weakly acidic is applied to solutions, and not applied to acids themselves." It then follows that a pH of 5 may arise from a solution of a weak acid, such as ethanoic acid, or a dilute (10^{-5} mol.dm^{-3}) solution of a strong acid such as hydrochloric; both solutions should be termed weakly acidic.

Historically the concept of pH arose from work on electrolytic dissociation pioneered by Arrhenius. Needing a measure of the tendency of a solution to supply H^+ ions, rather simply an acid or base concentration, Sörenson (1909) built on earlier work which recognized that measuring the concentration of hydrogen ions $[H^+]$ was more easily accomplished than it was for hydroxyl ions, $[OH^-]$, even in alkaline solutions, related by K_w, as described above. Sörenson's work recognized the importance of effective concentration of the hydrogen ions, rather than a simple acid concentration, on biochemical processes. Accordingly, he accommodated a wide range of possible values for hydrogen ion concentrations $[H^+]$ in the expression, which, in customary notation, may be given as: $\mathrm{pH} = -\log[\mathrm{H}^+]$ or $[\mathrm{H}^+] = 10^{-\mathrm{pH}}$, where 'p' represents 'power' or the exponent of 10. This means that one unit difference in pH corresponds to a ten-fold change in concentration, it also means that a higher concentration of hydrogen ions give a lower pH. In principle, Sörenson accepted the idea of negative values for pH, but hydrogen ion concentrations greater than $[H^+]$ = 1 mol dm^{-3} would be seldom encountered in his field, giving zero as a practical minimum for pH. Because of the importance of very low range hydrogen ion concentrations in natural buffer systems (Watters & Watters, 2006), biologists and biochemists readily adopted this idea of pH. However, chemists such as Clark (1928) spoke out about the counterintuitive way it related increases in pH to decreases in acidity and this has continued to challenge modern students (van Lubeck, 1999).

According to Hawkes (1994), calculations with concentration instead of activity of hydrogen ions, can differ in the first decimal from those using activities and, referring to Sörenson's work, he continues: "It is ironic that the natural and inevitable misconception of this pioneer haunts our introductory texts nearly a century later, even though the authors have the benefit of a modern education." He claims that within a decade Sörenson had made a correction to a new term paH, where a is the activity of H^+, which later became shortened to pH. Hawkes (1996b) describes equally simplistic calculations with buffer systems as 'dangerous' because they are so misleading. Nevertheless, such calculations still abound in chemistry and biochemistry textbooks (Watters & Watters, 2006) and so are included in the current analysis of student difficulties.

3.4 RESEARCHER CONTEXT

In qualitative research “the researcher is the instrument” (Maxwell, 2005, p 37), inextricably bound with an ‘object’ of enquiry. (Lincoln & Guba, 1985, p 39). However, research demands “critical subjectivity” (Maxwell, 2005, p 38). Moreover, Solomon (1993a) cautions that, despite researchers attempting to be disinterested observers, their particular perspective nevertheless frames their observations and interpretations, as was the case in the present study. Accordingly, my personal context will influence hypotheses, insights and validity checks and is outlined next.

In South Africa, chemistry comprises half the high school physical science curriculum. During my ten years experience in high schools, with English as the medium of instruction, I taught an operational model focusing on macroscopic properties of substances to junior classes. The Arrhenius model featured in Grade 10 for students who had chosen the physical science option, but was largely limited to strong acids and bases. The final school year (Grade 12) highlighted the Brønsted model, and applied it to acid-base strength, choice of indicators for titrations with weak and strong acids and bases, and hydrolysis of their salts. The curriculum also included calculations for titrations and pH (only with concentrations and assuming 100% dissociation).

As an experienced and reflective teacher I knew there were aspects of the curriculum where many cohorts of students had experienced similar difficulties, regardless of how carefully I presented the topic. Based on student feedback concerning specific problems each year I would incrementally change course material. Acid-base chemistry was one such topic. How was I to explain that water was an acid when clearly its pH was 7? One day we would use sodium hydroxide as a base in a titration, with the whole formula unit in a calculation and the next day a student would be confused about whether Na^+ ions were a conjugate acid of sodium hydroxide. Sometimes I too felt confused, despite having access to internationally published textbooks. In retrospect, I realise that I had been presenting hybrid models. My greater insight has been gained from science education journals and not textbooks or general professional magazines for teachers. My dim view of textbooks is affirmed by recent content analyses of the acid-base topic in textbooks. A preponderance of hybrid acid-base models was found in textbooks published in English (de Vos & Pilot, 2000; Furió-Más *et al*, 2005), Spanish (Furió-Más *et al*, 2005), Swedish (Drechsler & Schmidt, 2005a) and Greek (Kousathana *et al*, 2005). My experience has been valuable in gaining the following insights:

1. I needed to listen to what my students found troublesome;
2. course material changed accordingly, often subtly and usually incrementally, in response

to my growing insight into their difficulties;

3. Textbooks were often a poor resource for subtleties in conceptual knowledge that were troublesome; science education literature was more useful; and,
4. It is exceptionally easy to slip into teaching a hybrid model.

These insights help frame my interpretation of results in the present study.

3.5 STUDENT AND COURSE CONTEXT

Both the student and course context, for which data for this research were obtained, cannot be clearly described, as both varied considerably from one study to the next among the research papers analysed in this study. Thus, unlike in most other science education studies, data on student conceptual difficulties were obtained from a wide range of student contexts and courses from different institutions world-wide. However, both these contexts clearly affected the results of the study and thus cognisance should be taken of this factor even if it could not be well defined.

When determining criteria for including or excluding a particular study into the analysis, conscious choices were made for the following reasons. As explained in Section 2.2 of the literature review, student conceptual difficulties are remarkably consistent around the world, so there was no reason to be exclusive with regard to a particular culture, language or ethnicity. Furthermore, the same section shows that these conceptions are tenacious, despite good instruction, and may persist into adulthood. In Section 3.2.4 it was argued that a model developed in an earlier historical context or learned earlier in a student’s career may retain its relevance in certain modern contexts; I have regarded such models as cumulative knowledge, rather than one replacing another. Consequently, I treated research on conceptions of ‘simpler’ models gleaned from studies among older students, even at tertiary level, as indicating conceptions formed earlier in students’ careers. It follows that there was no reason to circumscribe a particular age group, provided the students had already been taught the relevant model. The only major restriction was in terms of the chemistry context which excluded conceptions of the Lewis model because of its usually being reserved for tertiary courses (see Section 3.3.4).

3.6 SUMMARY

In summary, the main aspects of the contextual framework are presented here. The research falls into a naturalistic paradigm, anticipating qualitative data on student conceptions, which requires comparison with scientifically accepted statements to gain acceptance within the science community.

Within an educational framework of constructivism, students all form their own unique understanding of concepts which may or may not be at odds with those recognised by the scientific community. Meaningful learning of chemistry may require explicit teaching. I anticipate that student conceptions may lack the nuances of expert knowledge which includes the relevance of different models for different contexts.

The chemistry context will focus on an operational model for acid-base chemistry as well as two historical models. These are the Arrhenius model hydrogen or hydroxide ions in solution, with the Brønsted model focusing on particles which may act as proton donors or acceptors. The concept of pH is both operational and theoretical with some controversy over whether to include simplistic calculations in a curriculum

Student and educational contexts will be determined by the research reports which arise from the search, but there will be criteria to narrow the search to exclude conceptions of the Lewis model. The researcher is an experienced chemistry teacher who has already found it necessary to adjust curriculum materials according to her student conceptions.

CHAPTER 4
METHOD DEVELOPMENT AND RATIONALE

4.1 INTRODUCTION

The literature review (Chapter 2) indicated a deficiency of reviews and syntheses of student difficulties with acid-base chemistry and of sound, research-based textbooks. To help meet these needs a critical analysis of existing research was proposed. According to Browne and Keeley (2004) critical analysis is founded in asking the right questions in order to reach an objective of improved conclusions, and this critical analysis entails five main research questions. This chapter shows the reasoning behind choices of research methods (partially informed by the theoretical framework given in Chapter 3) which were used to answer five research questions and their corresponding sub-questions. It starts by outlining some shortcomings of existing methods used to review research in student conceptions, and then shows how a research protocol was developed with the rationale behind selection of specific approaches.

4.2 EXISTING RESEARCH METHODS

Few reviews of student conceptions and difficulties in any chemistry topics have been published this century despite the continual appeals noted in the literature review (see Section 2.4.5) and the considerable growth in the literature on studies of student conceptions (Tsai & Wen, 2005). The quality of these reviews varies considerably and of six that were published recently on chemistry conceptions, all have shortcomings, as shown below.

Kind (2004, p 5) aims to “bring together research on students misconceptions in chemistry”. She summarises research findings under broad topics that cover much of a school chemistry curriculum, together with implications for teaching, which will be useful for educators. However, the breadth of her work precludes an in-depth review and there is no quality evaluation of the studies. Furió *et al.* (2002) simply give a brief summary of five main student difficulties with the mole as part of their review of teaching and learning this topic. Özmen’s (2004) historical narrative of research into student misconceptions about chemical bonding gives separate tables for the main knowledge claims from each article. There is no quality evaluation of the research and little effective synthesis, despite this being the stated aim of the paper. More detail is shown in two recent reviews with a similar format: Çalýk *et al.* (2005) in solution chemistry and Ünal *et al.* (2006) in chemical bonding. Both groups analyse the aims of the reports, research methods for the student conceptions and the main knowledge claims from the reports under broad topic headings, and then give recommendations for teaching, learning and curriculum development. Çalýk *et al.* also discuss the conceptions according to the probable source of the conception. However, neither group gives reasons for inclusion or exclusion of particular studies. The studies included in their reviews range from those published in international peer-reviewed science education journals to regional journals and doctoral theses, Çalýk *et al.* also include unpublished reports while Ünal *et al*. also incorporate articles from professional journals for teachers and conference reports available through the World Wide Web. Only Çalýk *et al*. define the time frame for the chosen publications. Moreover, in both studies the descriptions of student alternative conceptions show little further synthesis beyond the individual student quotes or descriptions from the original authors. All of these reviews give little more than a content analysis of existing research claims.

Liu (2001) goes much further than content analysis in his synthesis. Using a phenomenographic perspective, he constructs digraphs, which are directional and hierarchical concept maps, of student conceptions from prior research studies. The digraphs are then used to distil out the core student conceptions of matter arriving at seven hierarchical categories for these, from naïve to something close to scientific. Liu specifically did not aim to include all possible reports, as he wanted to establish the validity of the proposed method, so he focused on quality work selected only from peer-reviewed journals. Although there was no stated time-frame for his review, nine research studies were chosen to cover a wide range of research methods, student ages and socio-economic or cultural backgrounds. This process involved two researchers and Liu acknowledges its time-consuming nature when compared with a more intuitive synthesis.

Research methods reported in these reviews show a number of shortcomings with respect to the current aim of critical analysis of literature on student conceptions. Firstly, it needs to be focused on a specific topic. Then it needs a clear protocol for searching and screening of publications. In this regard, Torgerson (2003) indicates that in a systematic review, protocol should include the scope of the review, strategies used to search comprehensively for and then screen publications, methods of data extraction and quality appraisal. Certainly none of the reviews above would meet these criteria, although, to be fair, they did not claim to be systematic reviews. Nonetheless, critical analysis requires transparency (Wallace & Wray, 2006) which I interpret as protocols indicating a reproducible research process. A third shortcoming evident in the reports was the lack of effective synthesis by all researchers except Liu (2001); however his aim differs from mine. Useful protocols from the reports include a matrix summary of research methods (Çalýk *et al.*, 2005; Ünal *et al*., 2006) and concept maps (Liu, 2001). For all other aspects, due to unavailability of suitable methods for my proposed analysis, it was therefore necessary to look more widely for protocols or for certain aspects to develop my own.

4.3 MAIN PHASES IN THE RESEARCH PROTOCOL

As the research protocol is described, I consider research questions and sub-questions in sequence, taking the reader through each relevant phase, describing the steps in method development, the reasoning behind chosen procedures and the final details of the methods chosen for each phase. However, Research questions 2, 3 and 4 were considered in parallel as they had the same data sources and only later was it possible to decide under which category the difficulties fell.

To help readers assimilate the final research process, it is shown as a flow diagram (Figure 4.1). This figure is given in a flip-out format so that it can be easily referred to when reading different parts of this dissertation. The overall protocol has five main phases, as shown downwards on the flow diagram, namely *selecting* sources of data, extracting and *categorising* the data, followed by *comparing* data segments which enabled a *synthesis* from the data, which is finally *interpreted*. The phases are based on recommendations from McMillan and Schumacher (1993, p 482-484) and sometimes ran parallel to each other as these authors suggested. Furthermore, three targets of analysis, that is *research reports*, *student difficulties* and *propositional knowledge statements* were considered; these are shown from left to right across the flow diagram. It can be seen from the flow diagram that Research question 1 focused on the research reports. For all of Research questions 2, 3 and 4, sub-questions a and b focused on data for student difficulties, while sub-question c considered propositional knowledge statements. Finally, Research question 5 interpreted the propositional knowledge statements.

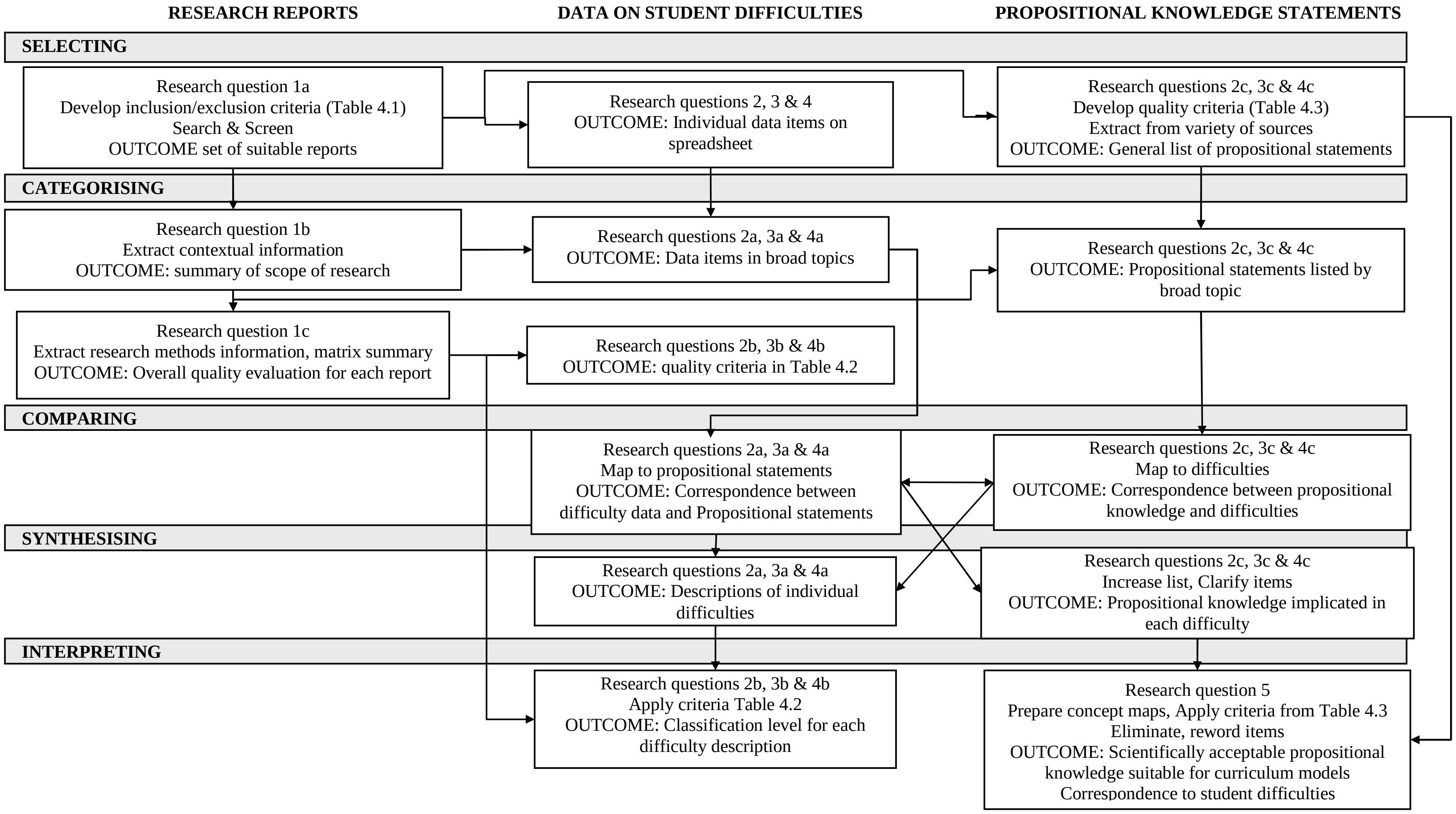

Figure 4.1 Flow diagram to show the overall research protocol

4.4 RESEARCH REPORTS SUITABLE FOR CRITICAL ANALYSIS

Methods described in this section address Research question 1: *What is the nature of research published on student difficulties with acid-base chemistry?* Protocols for a systematic review guided choice of methods, which should show replicable and effective processes for the stages of searching, screening, finding the scope of research, and quality appraisal of data (Torgerson, 2003, pp27-28 & 34-39). In order to analyse research into student conceptual difficulties in acid-base chemistry, it was necessary to first define three sub-questions, which are:

1a) Which reports give suitable research data on student conceptual difficulties in acid-base chemistry?

1b) What is the scope of this research?

1c) What is the overall quality of this research?

These sub-questions were each addressed in sequence, as described in the following sections. The protocol corresponds to the left hand portion of Figure 4.1.

4.4.1 Developing a search strategy and inclusion/exclusion criteria

Research question 1a was addressed through a variety of search techniques: electronic and hand searches and personal contact, as recommended by Bennett *et al.* (2005b) followed by screening using criteria developed by the researcher. Searching entailed firstly obtaining papers cited in published reviews (Kind, 2004, and Garnett *et al.*, 1995) then pursuing appropriate references from these cited papers. Next, an extensive search of academic databases (Academic Search Complete, ERIC and PsycINFO) was carried out. The literature review (Section 2.2) showed that a variety of terms can be used to describe student difficulties. Consequently, a variety of keywords and phrases were used in the search, which were: chemistry, acid/s, base/s, Brønsted, Arrhenius, student understanding, student conception/s, alternative conception/s and misconception/s. Then the same keywords were also used with the Google Scholar search engine (www.scholar.google.com). A third aspect of the search entailed systematically searching (by hand or electronically), as far back as 1978, the indexes and tables of content from science education journals available through the University of KwaZulu-Natal library. These included *International Journal of Science Education, Journal of Research in Science Teaching, Science Education, Journal of Chemical Education, Chemical Education Research and Practice* and, finally, *Research in Science Education*. Additionally, I was fortunate to be able to obtain some pre-publication copies of research reports through personal contacts. The abstracts of all suitable papers were scrutinized and if possibly suitable, hard copies were obtained. Finally, where authors of these papers had cited work that might have been suitable, these too were obtained. I judged the search had reached saturation point when further iterations of the process showed the same reports. This search took place between May 2006 and January 2008.

As discussed above, inclusion or exclusion of a study for a review should be based on clear criteria (Eybe & Schmidt, 2001; Bennett *et al.*, 2005b). The review publications described earlier (Section 4.2) had not suggested any suitable criteria, so it was necessary to derive my own. These were driven by the research aim and first research question, and guided by the theoretical framework and advice regarding systematic reviews (Torgerson, 2003; Bennett *et al.*, 2005b). Chosen criteria are given below in Table 4.1 (in flip-out form for readers' convenience) followed by the rationale behind the choice of each criterion.

Table 4.1 Inclusion and exclusion criteria for research publications

	Aspect	Inclusion if research includes:	Exclusion if Research is limited to:
1	Chemistry concepts	Acid-base reactions	Underlying principles, e.g. equilibrium, formulae Redox reactions of acids or bases Applications of acid-base chemistry, e.g. environmental or physiological
2	Acid-base models	Operational model (macroscopic properties) Arrhenius & Brønsted.	Other models, e.g. Lavoisier (historical), Lewis (not generally high school)
3	Type of knowledge	Conceptual knowledge	Isolated facts, e.g. indicators colour
4	Type of students	Any of: Elementary to post-graduate students, and teachers	Laypersons, other professionals
5	Research aims or questions	Probing for, or identification of student conceptions in an educational setting, pre- or post- instruction	Purely quantitative studies on prevalence or achievement. Instructional programmes
6	Type of research data	Student quotes or author knowledge claims about nature of conceptions, not previously published by the authors. Data of similar nature, from publications which are not available	Textbook quotes
7	Publication date	January 1978 to December 2007	Before January 1978 and after December 2007
8	Language of Publication	English	Other languages
9	Type of publication	Journals, available through academic libraries in South Africa or electronically Conference Papers published on www.	Theses, Conference proceedings not freely available on www or through South African academic libraries

Criterion 1

A narrowly focused research question is recommended by Torgerson (2003) and Bennett *et al*. (2005b). Accordingly, this study was limited to student difficulties in acid-base chemistry. Although these could be caused by problems with underlying concepts (Furió-Más, *et al*., 2007), such difficulties with more fundamental ideas such as distinguishing a chemical reaction from simple mixing, understanding the nature of chemical equilibrium or writing chemical formulae were not investigated. Redox reactions of acids or bases require different models for explanations to those described in the chemistry context (Section 3.3), so they were excluded; as were environmental and physiological applications of acid-base chemistry. Despite the importance of such problems as acid-rain, it was judged too broad to also target environmental or physiological as well as chemical concepts.

Criterion 2

High school curricula seldom embrace the Lewis model of acid-base chemistry (Oversby, 2000a). In order to focus on high-school chemistry, where I had the most experience, only conceptions of the phenomenological or macroscopic aspects of acid-base chemistry, with the Arrhenius and Brønsted models used to explain the phenomena were included. Students entering tertiary education could be presumed to have studied and mastered these conceptions at high school (see Section 3.3).

Criterion 3

The search for data on student difficulties with acid-base chemistry also focused on conceptual understanding as described in Section 3.2.2 on meaningful learning. For example, isolated items of arbitrary knowledge such as the colour change of particular indicators would not be included as these would need to be learned by rote, whereas understanding how indicators work and the choice of indicators for titrations of weak acids or bases could be included.

Criterion 4

Previous studies into student conceptions were included, provided they were not simply a survey of laypersons or other professionals such as nurses or engineers, who might not have received formal instruction in the relevant topics. There was no restriction on the age and educational level where conceptions were researched; indeed it would be advantageous to include a wide range of ages and contexts to ensure enough representative evidence for a conception (Grayson *et al*., 2001; Liu, 2001). Furthermore, as discussed under the 'student and course context' (see Section 3.5), student difficulties are widespread and tenacious, even into tertiary education, so that conceptions developed earlier in a students' career may still have an impact on how students filter new educational experiences later on. Consequently, this study could cover elementary school through to tertiary level and post-graduates, also including professional teachers. I include all these individuals under the banner of *students* when discussing *student difficulties,* as even teacher understanding is most likely to have developed during their student years.

Criterion 5

Any project that included an investigation into student difficulties, whether this was a primary aim or a necessary part of evaluating the effectiveness of an intervention has been included, provided there was suitable data available (see criterion 6). Pre-instruction data would need to be interpreted judiciously, as conceptual difficulties with chemistry models are not principally due to intuitive pre-conceptions (Taber, 2001a).

Criterion 6

With a view to gaining greater insight into the nature of particular student conceptions, rather than prevalence, I anticipated collecting any suitable qualitative data from the published papers in the form of student quotes or author knowledge claims, or perhaps in the form of distractors for multiple-choice items. Tan *et al*. (2002) considered alternative conceptions significant when there was a 10% incidence in their sample group, but this was not used as a criterion for this study, because research cohorts might be very small or an investigation only exploratory through open ended questions. However, data on the prevalence of a conception or student achievement data that was purely quantitative was deemed irrelevant in this review if it shed no further light on student understanding. Some authors cited and quoted descriptions of student difficulties from other publications – including internal reports from their own research group. These secondary sources have been included only when the original reports could not be obtained. We also excluded research focusing on poor presentation of this topic in textbooks (e.g. Drechsler & Schmidt, 2005a). While textbooks are undoubtedly one source of student misconceptions, such a content analysis represents a different research project. Similarly, research into the effect of different teaching strategies also fell outside this project. As with textbooks, this would constitute a separate project in itself.

Criterion 7

Publications over a thirty-year period were included. Driver and Easley's (1978) seminal work on student conceptions marks the start of this review and I looked for no further publications after December 2007. I included reports obtained through personal contact, at that stage 'in press', so their publication dates might be later than 2007.

Criterion 8

Only research published in English was included as I could not have done justice to work published in another language. In such cases, secondary reports on the work were accepted if they were available.

Criterion 9

Torgerson (2003) advocates including worthwhile smaller studies not published in the main journals, but still in the public domain. For logistical reasons, sources were limited to those available through academic libraries in South Africa or in the public domain on the World Wide Web. As a result, some research in dissertations, internal reports and certain conference proceedings was only available through secondary sources, or not at all.

As each research report became available, those that met the acceptance criteria for analysis were allocated numerical codes. These enabled me to later ‘tag’ each piece of data back to its source and to link all reports from one research group – important because they could involve overlapping data. The codes followed no particular order, simply being allocated in sequence as the reports were obtained. Information was initially recorded by hand on a separate printed form for each research report, and then summarized on a Microsoft Excel spreadsheet. This completed the *selecting* phase of answering Research question 1a, the results of which are given in Section 5.2 of the next chapter. Bibliographic information (according to column 1 in Table 4.2 below) for all the suitable research reports is given in Appendix 1. These reports were then used to categorise the scope and quality of the existing research in the next phase.

4.4.2 Categorising data on the research reports.

Qualitative research data should be interpreted within context (Lincoln & Guba, 1985, p 42) and, being guided by Torgerson (2003, pp 45-47) and Bennett *et al.* (2005), I extracted contextual information, as shown below in Table 4.2, from each published report, if it was published. A matrix, as suggested by Çalýk *et al.* (2005), was used to summarize the data. The data extraction and coding ran concurrently with the search process (see above).

Table 4.2 Contextual information extracted from suitable reports

Bibliographic information	Context of study	Research methods
Report code	Country	Cohort size
Search Source, e.g. ERIC or Google Scholar	Date of the study	Data collection instrument(s)
Author(s)	Research aims	Probes or interview questions given?
Year Published	Educational setting	In what form is propositional knowledge given?
Title	Pre-instruction or post-instruction?	
Full Citation	Participant details: e.g. age/ educational level, gender, ethnicity, socio-economic level	
	Acid-base topics	

During the categorising phase, by looking at the contexts covered by the body of research, I first sought an answer to Research sub-question 1b: *What is the scope of this research*? The results of this analysis are given in Section 5.2 of the next chapter. The next category of data concerned information on research methods in order to answer Research question 1c: *What is the overall quality of this research?* Codes indicating aspects of research methods such as the data collection instruments or nature of propositional knowledge given were used as suggested by Ünal *et al*. (2006). Sometimes, not all the desirable information was published. The research reports were then critiqued using guidelines published by Eybe & Schmidt (2001) to indicate the overall quality of the research. This is presented in Section 5.4 of the next chapter.

Assessment of the overall quality of the body of research informed the methods adopted for answering Research questions 2, 3 and 4 as described in the next section. Categories of acid-base topics informed the initial categories of student difficulties and propositional knowledge (Research sub-questions 2a, 3a and 4a, and 2c, 3c and 4c, see Sections 4.4.2 and 4.5.2 respectively**)** while the data on research methods were used in evaluating the stability of difficulty descriptions as described in Section 4.5.5.

4.5 SYNTHESIS OF DESCRIPTIONS OF STUDENT DIFFICULTIES

From reports meeting the acceptance criteria, as described in Section 4.4.1, data could be selected to answer three research questions. Research question 2 was: *What difficulties do students experience with* ***species*** *in acid-base chemistry?* In order to address this question, I needed to first frame specific sub-questions, thus: *2(a) What descriptions of difficulties with acid-base* ***species*** *can be synthesised from existing research data?* 2(b) *How stable are these difficulty descriptions across different contexts?* Research questions 3 and 4 involved exactly parallel questions and sub-questions concerning, respectively, acid-base ***properties*** and ***terminology and symbolism***. Initially all data for difficulties was treated as one set and was separated into these three categories only much later in the analysis. The analysis began with phases of selecting and categorising. Data was then compared to propositional statements to arrive at difficulty descriptions which were finally classified according to the stability of the description. A detailed description of the method development for these processes follows, corresponding to the protocol shown in the centre portion of Figure 4.1.

4.5.1 Selecting data on student difficulties

Studying the methods, results and conclusions sections of each report yielded four types of data on the student difficulties. Data segments were selected and coded accordingly, as follows:

- Distractors that students chose from multiple choice items (MCQ);
- Author’s knowledge claims (AU);

- Student or teacher quotes supporting these claims (SQ or TQ); and,,
- Further conclusions that I personally drew from the report (SEH).

Extracting all four data types in the list above could create some overlap, but this cross checking was necessary to verify the consistency of synthesis from the data. Moreover, it retained the texture of data provided by student quotes.

Computer techniques are useful for managing the volume of data entailed in qualitative research (McMillan & Schumacher, 1993, p 501) and Microsoft Excel had sufficient capability for this project. Data segments on student conceptual difficulties (in any of the four types above) were collected on a spreadsheet, each item being 'tagged' by the code for the research report, as well as the type of data (e.g. AU, SQ above). All individual data segments were typed verbatim, directly onto separate rows of the spreadsheet. Although quantitative data was not a focus of this synthesis, where authors gave the prevalence of a particular student difficulty, it was also included in a separate column. At the end of the selecting phase for Research questions 2, 3 and 4 there was an MSExcel spreadsheet with all the data segments as extracts from the original report, along with information about the original source, the type of data and possibly quantitative data. At this stage the column for the original source was 'hidden' so as to avoid prejudice concerning data originating from particular authors. In this way all data segments were treated equally, until later. This set of data was then used to synthesise difficulty descriptions.

4.5.2 Categorising data on student difficulties

A review of student conceptions requires secondary analysis of prior work in order to describe particular student difficulties more accurately (Grayson *et al*., 2001). In this regard, Torgerson (2003) and Cohen *et al.* (2000, pp 220-5) suggest meta-analysis in order to generalize from a range of studies and to identify inadequacies where further research is needed. However, their focus is on statistical methods applied to quantitative results. As Liu (2001, p 58) found: "there has been no methodology developed specifically for the purpose of synthesising findings of qualitative studies." The selection of recent reviews of work on student conceptions, which were outlined in Section 4.2, offer little further guidance on how to undertake the secondary analysis and synthesise overall descriptions, as except for Liu (2001), they barely go beyond documenting prior work. Furthermore, Liu's (2001) research used digraphs to distil out general trends in thinking, rather than individual conceptual difficulties. Another method was therefore needed and is discussed next.

The very nature of synthesis is to strip away the contexts so as to determine the common essence of the student difficulty (Liu, 2001). Inductive analysis, as described by McMillan and Schumacher (1993), is a method of analysing data which allows "categories and patterns to emerge from the data rather than being imposed on data prior to data collection" (p 480). In this way, categories are allowed to emerge from the data itself (Lincoln & Guba, 1985, pp 340-344).

The data had already been selected: as described in Section 4.5.1 each data segment concerning relevant quotes, with allied information, represented a row on a spreadsheet. In order to synthesise descriptions appropriate to answer research question 2a, 3a and 4a, I first needed some broad categories for the data. At the outset, the rows were first categorized according to representational systems used in chemistry. This seemed reasonable in terms of Johnstone's (1991) argument that many difficulties which students encounter in chemistry arise from their having to cope simultaneously with the systems: macroscopic, microscopic (later termed sub-microscopic, e.g. Johnstone, 1999) or symbolic. Furthermore, Nakhleh and Krajcik (1994) had used similar broad categories of difficulties. Data entries from all the research reports were then combined, in no particular order, onto three spreadsheets; one for each representational system. These initial spreadsheets were, however, exceptionally long and cumbersome, with many difficulties overlapping categories and hence needing to feature on more than one sheet. An alternative method for categorizing the data was suggested by the initial scope of existing research which had included notes on the broad acid-base topics covered in each research report (see Section 4.4.2). Thirteen topics proved to be suitable for initial categories of data and are shown below (see Table 4.3). These reflected broad categories which suggested species, processes and representations (see Section 2.5.2).

Table 4.3 Initial categories for difficulty data segments

Species	Processes	Representations
Acid/base definitions	Macroscopic properties	Chemical formulae & equations
pH	Neutralization	Aqueous equilibria
Salts	Indicators	Acid-base strength
	Heat of reaction	Conjugate acid-base pairs
	Everyday applications	Polyprotic acids

Having inserted another column into the spreadsheets I used one of the words or phrases above for each row, sometimes repeating the row if two or more words were applicable. For instance the student quotation "pH is inversely related to harmful" (Nakhleh and Krajcik, 1994) related to both pH and everyday applications. Sorted in this way the data was much more manageable, and I subsequently abandoned the initial macro/ sub-micro/ symbolic classification. At the end of this stage data for Research question 2a, 3a and 4a had been selected, and categorised. To reduce bias when treating data from different sources, the spreadsheet column with the source paper code was kept hidden during the next phase of comparison.

4.5.3 Comparing data to synthesis descriptions of student difficulties

A method of constant comparison was used to further classify data. This involved putting data from different studies side by side (Lincoln & Guba, 1985, p 203), which allowed synthesis and honing of a description for each student difficulty. In this regard, the use of numerical codes proved useful as it enabled rapid grouping of data into smaller sets, each set indicating a similar difficulty with only contextual differences.

Numerical codes used in this process represented individual statements of scientifically accepted propositional knowledge (derivation of these propositional statements will be described in Section 4.6). My idea of categorising data segments in this way arose from the association of student conceptual difficulties with a limited or inappropriate propositional hierarchy or LIPH (Novak & Gowan, 1984; see Section 3.2.3). Drechsler and Schmidt (2005b) used a similar, but less detailed, idea to categorize inappropriate or mixed models which students had used in their explanations. By coding difficulty data in this way I was indicating a proposition that, if missing or inappropriate, could give rise to the difficulty. I presupposed that individual data segments for a common difficulty would end up mapped to the same proposition. Working with a provisional list of propositional knowledge statements, I allocated at least one numerical code to represent a propositional statement to each difficulty data segment. In this process I drew on my teaching experience, imagining I was correcting students' work, to identify scientifically appropriate ideas which were missing or incorrectly applied. For example, "milk is a base" mapped to the statement: *milk contains acidic substances.* In some cases more than one propositional statement was needed as illustrated by the student quotation "Water as an alkali is difficult to conceive" (Schmidt & Volke, 2003) which mapped to three propositional statements, specifically: *Alkali is an alternative term for Arrhenius bases, Brønsted bases: examples do not include Arrhenius bases* and *Brønsted bases:*

examples include the molecules H_2O*.* Unless I was able to interview the student, or it was clear from the research report, I would not know which aspect(s) might be missing or inappropriate in the student conceptual framework so I erred on the side of caution by giving all four. I thus anticipated a 'many-to-many' mapping as illustrated below in Figure 4.2. Some propositions may not be implicated in any difficulty (P_1); others may be mapped from only one difficulty (P_3 and P_5), or even from several difficulties (P_2, P_4 and P_6). Furthermore data on difficulties may only map to one proposition (D_4), or to several (D_1 to D_3).

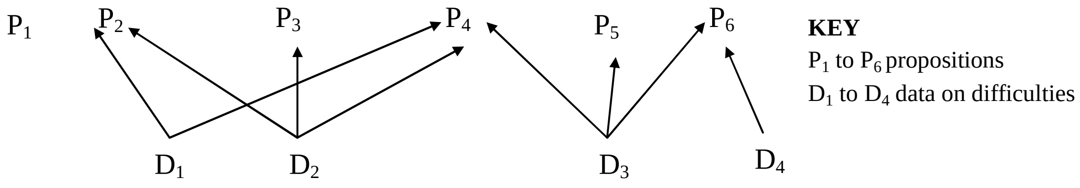

Figure 4.2 A 'many-to-many' mapping of student difficulties to propositional statements

Each difficulty data segment now had a unique numerical code and it was possible to sort the spreadsheets according to the two columns, namely topics and codes for propositional statements. I termed this stage the 'fine-sort' as categories had become much finer. Similar student difficulties were thus grouped and their commonalities quickly became evident. This was the end of the comparing phase for Research questions 2a, 3a and 4a. Data were now sorted so that smaller, more manageable groups were mapped to a code for a particular propositional statement. At this stage the "hidden' column on the spreadsheet with codes representing the reports from which the data segments had been extracted was revealed and any data segments which were duplicates were deleted. The next stage was to synthesise a single description for a difficulty from each group of data.

For the synthesis stage, it was a pleasant surprise to find that, not only had the propositional statements allowed easy sorting, they also facilitated synthesis of a description showing the essence of a difficulty. Sometimes, it was only necessary to reverse the sense of propositional statements. Thus, in most cases, a concise description of the particular student difficulties in each category could be synthesised in a single step. To illustrate: The data for difficulty R10 (see Section 8.3.2.3) mapped to the two propositional statements:

- The general Brønsted reaction scheme applies to many different types of reactions.
- Brønsted model, neutralization can be represented as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$

Reversing the sense of the statements led to the difficulty description: T*he general Brønsted reaction scheme shows neutralization.* Sometimes further iterations were needed if the preliminary difficulty description suggested further modification of propositional statements which then in turn, helped further hone the description. It was thus possible to use the propositional statements to both sort the data and to sharpen descriptions of the student difficulties, thereby better encapsulating their nature.

Decisions on how broadly to group data were guided by Grayson *et al.* (2001). They show how an inductive analysis of student responses was used to derive descriptions of difficulties. They describe an instance of one overall difficulty which could be further differentiated into two conceptions, each indicating different student reasoning difficulties so requiring different remedial strategies. However, variations within each difficulty could be addressed by the same strategy so further subdivision of the difficulties into sub-categories served no useful purpose. In a similar, but reverse, fashion I aimed to combine individual difficulty descriptions and synthesise a description linked to a common set of propositional knowledge, indicating a common difficulty. If the propositional knowledge was substantially different, it was likely to indicate a separate problem with corresponding implications for teaching. At the end of this phase there was a set of difficulty descriptions that were decontextualized and for which there had been no quality checks. These two aspects were addressed in the final phase, interpretation.

4.5.4 Interpreting difficulty descriptions

Synthesis should not lose sight of the research that led to the data, so it must look at the whole study, not only the data. In this regard, Lincoln & Guba (1985, p 41) emphasise that in naturalistic enquiry data interpretation should be negotiated with human sources in the study. This was not practical in my study. However, central to secondary analysis is the idea of a common pattern emerging, in which case “the conclusions may be stronger than the component studies” (McMillan & Schumacher, 1993, p 144). Nevertheless, these latter authors warn against combining ‘apples with oranges’ and they stress that conclusions should make conceptual sense. They also emphasise looking for discrepant data (p 391). Accordingly, as I wrote about each difficulty in the results chapters, I returned to the original reports, rereading each one afresh to be assured that I had caught the essence of the research in its particular context, asking myself if the description made sense in that context and if there were any anomalies.

Three major categories of difficulties are presented in chapters 6, 7 and 8. The first major category: **Difficulties with the species in acid-base chemistry** will be found in Chapter 6. This chapter covers the notions which students have about matter classified as acid, base, neutral, salts, or amphoteric species. Grouping descriptions of student difficulties with more concrete entities into one category indicates the foundational concepts that may present difficulties. The second major category, **Difficulties with acid-base properties**, represents more abstract, process concepts and will be covered in Chapter 7, where the primary focus is on acid-base properties and processes including neutralization. The last major category: **Difficulties with terminology and symbolism in acid-base chemistry** covers difficulties with symbolic representation, which may be a technical term, or chemical or mathematical symbols, and is presented in Chapter 8. Difficulties in each chapter are given corresponding prefixes. To elaborate, difficulties S1 to S10 are those concerning species, difficulties P1 to P26 concern the general properties and processes while difficulties R1 to R17 relate to difficulties with representations. The final interpretation of the difficulty descriptions which had been synthesised involved considering the stability of these descriptions across the range of contexts in the original research, according to Research sub-questions 2b, 3b and 3c. This aspect is described in the next section.

4.5.5 Quality of reported research

Criteria for inclusion or exclusion of a publication into this analysis (see Section 4.4.1, Table 4.1) made no mention of quality of research reported in these publications. However, critical analysis should evaluate the merits of and faults in the research underpinning knowledge claims (Wallace & Wray, 2006) such as difficulty descriptions as reported here. In this way it aims to achieve, not only “some level of understanding” typical of naturalistic enquiry (Lincoln & Guba, p 37) but also estimate the level of understanding (see Section 3.1). To this end, addressing the first research sub-questions (2a, 3a and 4a) had given descriptions of individual difficulties, and from Research question 1c there was data on research rigor concerning these difficulties (Section 5.4). Finally, a more detailed analysis of the sum of research concerning specific difficulties was needed; this section shows how answers were sought to Research sub-questions 2b, 3b and 4b: *How stable are these descriptions across different contexts?* In this regard, a description which is substantially unchanged across differing educational and chemical contexts is presumed to be stable. Some challenges to this goal are discussed next, followed by methods adopted to accommodate these problems.

Researchers should be aware that what they call student conceptions are really the researcher’s conceptions of the student conceptions (Duit & Treagust, 1995; Johnson & Gott, 1996; Clerk & Rutherford, 2000; Liu, 2001). In the same way, when introducing a book on children’s informal ideas in science, Black and Lucas (1993, p xii) suggested “only partly tongue in cheek” the title could have been “Alternative misconceptions of children’s scientific ideas”. If, as

Marín *et al.* (2004, p 427) suggest, the term *conception* refers to “replies that show a certain degree of regularity and are an observable manifestation of student cognition”, then what is needed are ways of distinguishing ideas that represent significant thinking of an individual or group from ad-hoc responses that may be generated under pressure of an interview or test (Driver, *et al.,* 1985). Moreover, data collected by different methods may be cross-checked and merged to give a more comprehensive picture through triangulation (Lincoln & Guba, 1985, pp 108 & 306; McMillan & Schumacher, 1993, p 386). As this project is a secondary analysis which entails interpreting prior work, this was a challenge, as not all research reported such rigor. However, internal validity can be seen as relative, rather than absolute. The degree of validity being determined by particular aspects of the reported research (McMillan & Schumacher, p 391), as outlined next.

4.5.5.1 Descriptions of student conceptions, some validity threats.

Research work which proceeds directly to multiple-choice items to ‘establish’ student alternative conceptions needs to be treated cautiously. Accordingly, some validity threats in the descriptions of student conceptions are discussed next. Research probes should only become more focused as greater insight into the nature of the student difficulty is achieved. As a specific example, Grayson *et al.* (2001) began their research with open-ended or free response written probes, followed by structured interviews to uncover greater understanding of the student reasoning, which they then used to construct multiple-choice items incorporating free response justifications for the choice. Treagust (1995) used a similar sequence to arrive at two-tier diagnostic instruments; that is, linked pairs of multiple-choice items requiring both an answer and an explanation. Even so, Chiu (2007) has some reservations about these two-tier items because the second-tier includes only a limited selection of the possible reasons for the first choice, none of which may represent the student’s actual reasoning. To alleviate this problem, some workers include a further open-ended choice; in which learners can provide an alternative reason should they feel none of the second-tier statements are correct (Schönborn & Anderson, 2008b). Multiple-choice items constructed in any of these formats allow the ease of collating and categorizing responses to focused probes in large populations, while still fostering some validity. On the other hand, poorly constructed multiple-choice items show a range of other problems. For instance they may “direct the students’ thinking towards the examiner’s point of view” (Dhindsa, 2002, p 19). This is illustrated by Schmidt and Volke’s (2003) report of a student who showed in a subsequent interview that he did not really believe his earlier response to a written probe. Other potential problems with multiple-choice items are discussed in more detail by Anderson (2007) and Schönborn and Anderson (2008b).

The content validity of research probes also needs to be evaluated. For example, Eybe and Schmidt (2001) caution that including several alternative historical models in one set of distractors for a multiple-choice item could introduce ambiguities, with corresponding difficulty in judging answers as correct or incorrect. This weakness had also been evident in physics education research, prompting Pushkin (1996) to argue for modern terminology when investigating student conceptions rather than reinforcing outdated concepts.

The whole investigation, including interpreting student responses, should take place on neutral ground, which should be derived from the student’s, rather than the researcher’s, frame of reference. In their retrospective analysis of studies about student conceptions in the particle nature of matter, Johnson and Gott (1996) used this basis to challenge some authors’ interpretations of data. In a similar way, Domin (1996) questioned the validity of reporting an author-generated concept map of a student’s cognitive structure (Nakhleh & Kraijck, 1994). However, the research authors explain: “our findings that students overwhelmingly used the macroscopic representational system in talking about acids, bases and pH is supported by our analysis of the titration protocols of the same study in which students apparently thought of little else but procedure and macroscopic observations, even when performing a familiar titration routine” (Nakhleh & Kraijck, 1996, p 937). In this way they could subsequently defend their interpretation, which had been triangulated from interviews and a protocol analysis.

In summary, research rigor for studies in student difficulties will be enhanced by progression from open-ended probes to more focussed probes. These should be carefully phrased, so as to not actually introduce misconceptions or historical ambiguities. The probes themselves should be within a student’ frame of reference, as should all interpretation of responses. In their search for quality criteria in chemistry education research, Eybe and Schmidt (2001) found such rigor sadly lacking in much of the published material. However, not wanting to summarily exclude data from less rigorous but useful studies, I sought a different solution for this study. Instead of looking only at the research within one study, commonality between multiple studies in a variety of contexts was sought as is outlined next.

4.5.5.2 A four-level framework to classify difficulty descriptions

To evaluate the stability of student difficulty descriptions synthesised from these studies, a hierarchical classification framework was developed. It was based on previously published work and extensive discussion with experienced science education researchers. One source was a classification system which Andersson (1990) proposed in a review of student conceptions of matter. His suggested categories included: (I) student quotes, (II) conceptions derived from a single study, (III) conceptions based on several studies, and (IV) a general description of the conception. However, he cautions against losing finer detail as descriptions become more general and argues that descriptions at all levels are valuable for teaching. Furthermore, Andersson gives little guidance as to how to achieve these descriptions of student difficulties.

Along the same lines of gathering increasing evidence about a particular difficulty, Grayson *et al*. (2001) propose a similar framework which ‘moves’ descriptions of student difficulties through four levels based on cycles of increasingly focused data collection. These levels of descriptions are those which are: (1) Unanticipated as they arise unexpectedly through data collection, (2) Suspected on the basis of teaching (with only anecdotal evidence), (3) Partially established from one systematic investigation and (4) Established from systematic investigations in different contexts. Anderson and McKenzie (2002) later used the Grayson *et al.* framework to evaluate published research information on student difficulties, used to populate their online resource (http://www.card.unp.ac.za/home.asp) for conceptual and reasoning difficulties. Like Andersson’s framework, Grayson *et al.*’s acknowledges the benefit of several complementary studies to increase the accuracy of a difficulty description. While Grayson *et al.* give greater detail than Anderssson of how to use their framework, it was still not perfectly suited to the current project concerning published research findings.

During discussions with science education research colleagues about the Grayson *et al.* (2001) framework, two concerns were expressed. First of all, Level 1 represents unanticipated research data while Level 2 corresponds to difficulties that have emerged from prior teaching experience rather than research. Thus in a single investigation a difficulty could ‘move’ rapidly between Levels 1 and 3, bypassing Level 2. Secondly, in this framework there is a large difference between Levels 3 and 4. Thus the hierarchy finally chosen for the current study was an attempt to address these problems by modifying the Grayson *et al.* (2001) framework in two ways. Firstly, Levels 1 and 2 were interchanged, giving research rather than anecdotal evidence a higher standing. A second change instituted levels 3+, 3++ etc to show multiple contexts for a difficulty, which was not yet classified at level 4. The new framework thus includes evaluation of the amount and quality of all research on a conception, as well as the degree of insight this brings to the description. It is presented in Table 4.4 (on the following page).

The table shows that classification levels for a particular student difficulty improve from 1 (merely suspected) to 4 (established) as insight grows through research into the nature of the student difficulty. This increased insight is shown by the description of a student difficulty becoming more stable (or reliable), as shown by different data sources (triangulation) and the existence of the difficulty in multiple contexts. In other words, it is not merely idiosyncratic within a single student population.

Table 4.4 Hierarchical Classification Framework for Difficulty Descriptions

(based on Grayson, *et al*. (2001)

Level	Label	Insight into difficulty	Source of insight	Possible Uses
1	Suspected	Intuitive or subjective description	Teaching experience/ anecdotal OR Unanticipated data Not controlled data, e.g. unvalidated MCQ	Teaching and evaluation Research through free-response probes
2	Emergent	Description based on research, may vary between contexts	Some controlled research No triangulation reported	Teaching and evaluation Research: basis for a range of free-response probes
3*	Partially established	More explicit description, open to modification	At least one triangulated study Or identified separately in several independent studies	Teaching and evaluation Further Research: basis for a range of more focused probes
4	Established	Description is stable – it does not vary substantially between educational or equivalent chemical contexts	Triangulated studies in multiple contexts	Teaching and evaluation, Design of learning material Diagnostic tests, MCQ distractors for concept inventories Other Research, Prevalence studies, Cross-age studies

*Levels 3+, 3++, 3+++ etc were introduced to show the range of contexts studied in the research

This modified framework, as given in Table 4.4, was applied to interpret and classify the combined data on student difficulties reported in each published study. It is possible that results from a rigorous study may have been given a low classification (for example Level 2) if crucial parts of this information were not reported. In order to ‘move’ a description of a particular difficulty up the hierarchy, it was not enough to simply identify it in more contexts. Its description also needed to become sharper in order to show the essence of a difficulty, as shown by its universality and increased stability across different contexts. Where a student difficulty appeared in many contexts I verified that the new description was stable – that it appeared to encapsulate the nature of the student difficulty as it appeared in different contexts. Now and again a difficulty was reported from multiple contexts but still appeared to have a vague description. In some cases, further inductive analysis of the original data revealed that there were in fact two separate difficulties that could be identified, meaning that I had previously grouped the responses too broadly. In other cases, it was evident that there was not yet enough research to illuminate the essence of a difficulty, so its description remained at a lower classification level. Furthermore, it was important that different contexts were truly independent studies. For instance some research studies included multiple-choice items based on published results, sometimes from a single cohort of students, taking these as accurate descriptions. As a result, these subsequent studies contributed no greater insight into the description of the difficulty; they only showed that other students also chose a particular response. Taking into account the quality of research, final classifications of individual difficulties is given in Chapters 6, 7 and 8, as each difficulty is individually described.

Where a stable description of the difficulty exists (Level 4 classification) it indicates that further research into its nature serves no useful purpose. In such cases the research focus should change; the description could form the essence of a distractor for a concept inventory (see Section 2.4.1) or perhaps research should investigate the underlying cause or evaluate a remediation strategy for the conception. Conversely, a low classification would show that the difficulty needed further research into its nature; for instance, showing its existence in other contexts or closer investigation into its nature in order to describe it more explicitly. After the difficulty descriptions were interpreted individually within the relevant research contexts, leading to evaluation of their stability on classification levels, Research sub-questions 2a & b, 3a & b and 4a & b had been answered.

Finally, I attempted to evaluate the effectiveness of the search and secondary analysis according to whether it illuminated a difficulty that had not previously appeared in review articles; Gabel and Bunce (1994), Garnett *et al.* (1995) and Kind (2004) being the chosen benchmarks. Certainly one would expect that difficulties which had high classification level based on data published before those dates should have been mentioned in the reviews. However, this evaluation had limited applicability as much of the research was published too late for these publications, and Kind’s review was very general (see Section 4.2). The final descriptions, together with each classification level and corresponding propositional statements, are summarized in tables in Chapters, 6, 7 and 8, which are followed by discussion of the research behind each description.

4.6 DERIVATION OF PROPOSITIONAL KNOWLDGE STATEMENTS

A need for statements of acceptable propositional knowledge to stand alongside descriptions of student difficulties had already been identified (see Sections 2.4.6 and 3.2.3). Consequently, the third sub-question to be addressed for Research question 2 was: *What statements of propositional knowledge are needed to address difficulties with* ***species*** *in acid-base chemistry?* Once again there were corresponding sub-questions for Research questions 3 and 4 involving acid-base ***properties*** *and* ***terminology and symbolism.*** In the previous section (4.5) I showed how data segments on difficulties were mapped to suitable statements of propositional knowledge, in order to help classify data from individual studies and then to hone synthesised descriptions of the difficulties. This section outlines the method, by which these suitable propositional knowledge statements were derived and evaluated which entailed, in part, constructing concept maps to show conceptual hierarchies.

The process involved firstly drawing up criteria for acceptable propositional statements, then once these were set, a general list of propositional knowledge statements was prepared from a variety of sources and sorted by broad topics. These statements were then used to help categorise data on difficulties, and at the same time propositional statements were resolved to show finer detail. Finally the set was evaluated and arranged in a conceptual hierarchy from which inferences concerning teaching and learning could be drawn. The following sections give the details of this process, which corresponds to the right hand section of Figure 4.1 (page 56).

4.6.1 Criteria for propositional statements

From the scope of the research reports deemed appropriate for this secondary analysis (see Section 4.4.2) I knew that some researchers had reported propositional knowledge. For instance, Nakhleh and Krajcik (1994) used a summary gleaned from senior secondary textbooks, while Ross and Munby (1991) based theirs on curriculum guidelines. However, some authors did not describe their source, leading me to question the scientific acceptability of some of their propositions. In particular, a concept map given as a standard by Botton (1995) includes a statement that Oversby (2000b) would consider a misconception. Moreover, the scope of the research (Section 4.4.2) showed that some authors gave no orientating framework of acceptable knowledge. However, according to Johnson and Gott (1996) it is naïve to presume that the underlying scientific ideas in science are universal or ‘unproblematic’. Such inconsistencies suggested that deriving a comprehensive list of suitable propositional statements would not be simple. Accordingly, I first drew up criteria for accepting these statements, which were guided by the literature on propositional knowledge.

From the literature I identified several potential problems with propositional knowledge. Firstly, according to Mintez and Novak (2000) propositional knowledge within a field of study should form a coherent whole, showing *consistency* by reconciling internal contradictions. These authors also contend that propositional knowledge should be agreed within the academic community of a discipline. However, Eybe and Schmidt (2001) caution that putting forward a "system of knowledge statements" (p 220) may infer that there is a single view of acceptable chemistry, rather than the system simply giving the frame of reference against which the researchers will compare the students' ideas. As already discussed (see Sections 2.3.1 and 3.2.1) the nature of science means that scientific conceptions are not fixed; they are human constructs and modern meaning for terms may differ from the original (Hall, 1930; Schmidt, 1991; Taber, 2002). Consequently, I anticipated not one set of propositional knowledge but several, each within the context of a particular historical model. Furthermore, each model should have *transparency* in that the propositions could be justified within the conceptual framework of the appropriate scientific paradigm.

A further problem was raised by Stains and Talanquer (2007) concerning the relationship between 'accepted' understanding and that which practitioners actually use. In particular, their interviews with university lecturers revealed a strong association and corresponding lack of differentiation between some pairs of concepts. For example, some staff associated the label compound with O_2, or N_2 because they were both molecular species, although scientists generally accept oxygen and nitrogen as elements. Furthermore, Bowen (2005) differentiates between "ready-made-science" or school science presented as unproblematic and "science-in-the-making" as practised by scientists, which is messy but needs to be defensible. Consequently, lack of agreement among scientists about particular propositional knowledge may present further complications. Nonetheless, there should be some *consensus* so that meanings are resonant with or shared by experts (Mintez & Novak, 2000), rather than being my own understanding.

A third possible problem is that expert chemists may reject conceptions which are deemed acceptable among school pupils, considering them incomplete or even incorrect. For instance, Taber (2002) notes that abbreviated definitions are often introduced to novices because they may only use a concept in limited contexts, but this could leave students unaware that their conception is not generally applicable. Moreover, Hawkes (1994) maintains that students tend to retain what they learn first, so an introductory qualitative description should lead correctly into the quantitative models that students will encounter later. However, as Nelson (2003) and Bucat (2004) argue, it makes no sense to plunge a novice chemist into a formal definition as agreed by the International Union of Pure and Applied Chemists (IUPAC). Nelson then makes practical suggestions of "*pragmatic* definitions" which are as simple yet precise as he could make them. In a similar manner, de Vos and Verdonk (1996) prepared a summary of the particle nature of matter in the form of propositional statements. They made no attempt to win the approval of expert scientists for this summary, because it was used to evaluate introductory school textbooks. Instead, the summary was agreed to be valid by science education researchers. This was the researchers' community of practitioners. Accordingly, I would seek something suitable for students, without being wrong in the view of expert chemists.

Mintez and Novak (2000) also emphasise *parsimony* which is evident when an individual understands a topic, so propositional knowledge should not include superfluous information such as extraneous explanations or unnecessary propositions in their conceptual structure. However, a fourth problem lies in Shulman's (1986, p 11) warning: "the representation of knowledge in the form of propositions has both a distinct advantage and a significant liability." Because propositions strip away the superfluous, they are economical but at the same time decontextualized. Furthermore, being discrete statements, they are hard to remember, especially as lists. Propositional statements are the 'bare bones', which teachers and textbook authors need to transform into learning experiences. Accordingly some way of integrating the statements would be needed.

The challenge in this study was therefore to outline acid-base models in sets of discrete propositional statements against which student conceptions might be compared, which could still be integrated into a whole. The statements should represent the different historical models authentically, yet be understandable and appropriate in the school context. They should certainly be acceptable to a community of practitioners, in this case chemistry education expert opinion. Notwithstanding de Vos and Verdonk's reservations mentioned above, ideally they should also be acceptable to expert chemists. Could such a coherent set of statements of acceptable knowledge reflecting the contexts of different historical models be compiled? This led to the fifth and final research question: *Does the set of propositional knowledge statements derived through analysis of student difficulties reflect appropriate knowledge for teaching and learning acid-base models?* In order to answer this question, two sub-questions were formulated:

5a. *How well do the propositional statements reflect curriculum models for acid-base chemistry?*

5b. *What are the implications of the propositional knowledge for teaching and learning acid-base chemistry?*

Accordingly, based on arguments given above, criteria given in Table 4.5 were developed for propositional statements relating to each acid-base curriculum model (see Section 2.1.3).

Table 4.5 Criteria for acceptable propositional statements

	Aspect	**Propositional statements should...**	**How it will be evaluated. Propositional statements will be....**
1	Pragmatism	Be age appropriate	Determined by the difficulties concerned Compared with curriculum statements
2	Parsimony	Avoid superfluous propositions and examples.	Phrased in terms of general principles, with specific applications given as examples to indicate prototypes and boundaries of concepts.
3	Consistency	Be coherent within each model.	Integrated as concept maps for each model.
4	Transparency	Maintain the integrity of the hard-core for historical models.	Able to define the context and limitations of each model.
5	Consensus	Be acceptable to chemists.	Checked against publications in chemistry education and chemistry and evaluated by expert chemists.

Propositional knowledge derived from mapping student difficulties would be evaluated against criteria representing five aspects of acceptable student understanding. By this means I would determine how well they met the ideal as shown in the final column, rather than give a dichotomous acceptance or rejection. The first criterion of *pragmatism* was introduced to ensure that statements are appropriate for students rather than experts. However, there was a problem because the age groups in this analysis were not restricted (see Section 3.5) – which age students should I consider? A solution, allowing me to accommodate many ages of students, would be to let the difficulties themselves guide the particular propositional knowledge statements, rather than starting the research by specifying propositional knowledge, as recommended by Treagust (1988, 1995). For example difficulties with an operational model would indicate statements at an operational level of macroscopic observations, appropriate for younger students. Conversely, difficulties with calculating pH of an extremely dilute solution, which would probably be encountered at tertiary level, would be addressed by propositional statements pertinent at that level. However, to address Research sub- question 5a, it was still necessary to evaluate whether these propositional statements represented the whole or only limited aspects of the acid-base topic as taught in high schools. Accordingly the set of propositional statements would be compared with three typical curricula (Ross & Munby, 1991; Nakhleh & Krajcik, 1994; Independent Examination Board, 1997). The first two publications give extensive propositional knowledge to represent acid-base topics as taught in high schools, the first as a concept map and the second as a set of propositional statements. The third publication outlines a South African curriculum that has been superseded, but it was retained in this analysis because the current South African high-school outcomes based curriculum does not feature acid-base chemistry as a distinct topic (Department of Education, 2003).

Next, according to Mintzes and Novak (2000), *parsimony* requires that the propositional knowledge focuses on the core principles of acid-base chemistry and that each application or example is there for a reason. For example Herron (1996) recommends that concept analysis requires specific examples and non-examples to indicate the extent and limitations of a concept as shown by Criterion 2. Criterion 3 involves internal *consistency* – the propositional knowledge defining a field of study should form a coherent whole. A concept map comprises a number of propositions, each linking at least two concepts. It is a useful way to ensure propositional knowledge is integrated without contradictions (Novak, 1996). Furthermore, concepts represented as nodes with attendant propositions will provide a context for the propositions. *Transparency* means that the propositions for a given model can be defended within the scientific paradigm concerned. This paradigm needs to be defined and its limitations made clear as in Criterion 4. Finally, to satisfy Criterion 5, *Consensus* or agreement within the community of chemists can be established through first checking propositional statements against original chemistry and chemistry education publications which distinguish the models concerned, then expert chemists can evaluate the propositional statements.

To ensure that propositional knowledge would meet the criteria given in Table 4.5, certain checks were instituted which ran concurrently with developing the list of propositional statements. Figure 4.4 below shows the processes of selecting, comparing and synthesising in diagrammatic form, with more detail than was possible in Figure 4.1; the next sections explain it further.

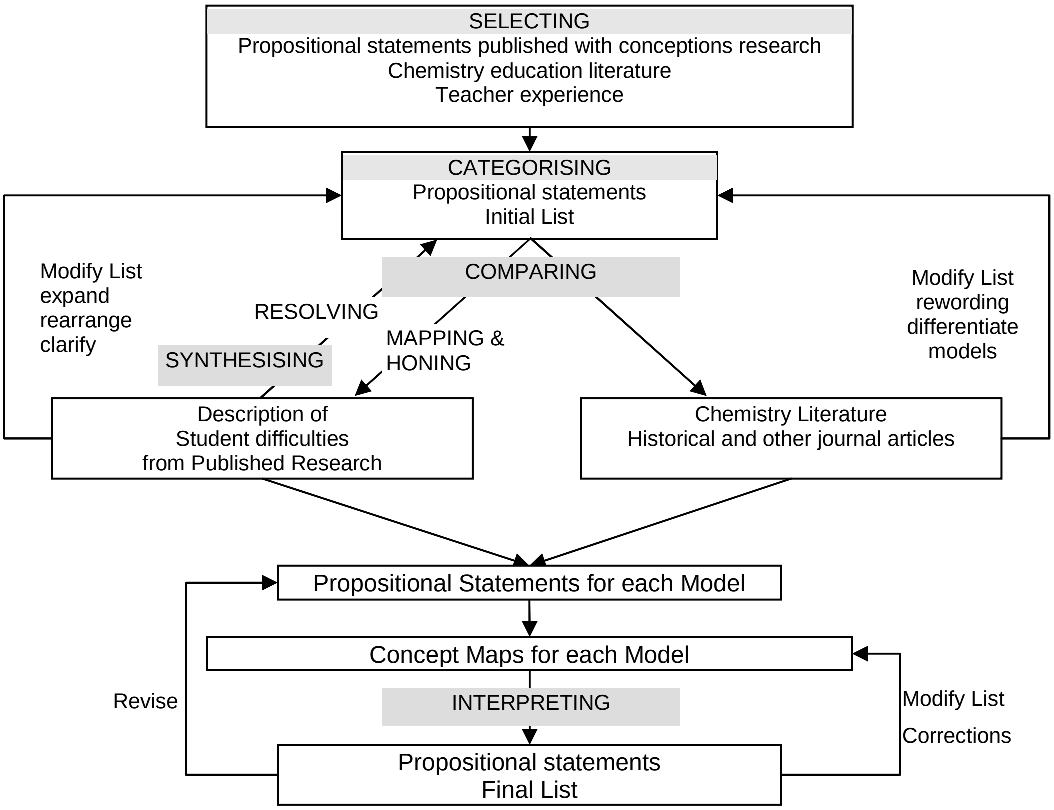

Figure 4.3 Flow Diagram to show derivation of propositional statements

4.6.2 Selecting the propositional knowledge statements

As mentioned in the previous section I allowed the difficulties to determine suitable propositional knowledge rather than starting with a fixed idea of what to include. At the outset, mapping between difficulties and propositional statements identified some of the required propositional knowledge. This process was found to be reciprocal and iterative. In many instances, mapping a student difficulty back and forth to propositional knowledge led to both clarifying and increasing the set of acceptable propositional knowledge statements. A starting point was any propositional knowledge given as being scientifically acceptable in the publications from which the data on student difficulties were extracted. For example Nakhleh and Krajcik (1994) gave their synopsis of textbook presentations concerning the general principles of the Brønsted acid-base model, separated according to four representational systems, which they term: macroscopic, microscopic, symbolic and algebraic. As already stated, not all authors were as clear as this, and some gave no orientating framework of acceptable knowledge. Where possible this information was extracted in one or more of the following five forms:

- Lists of separate propositions (only Nakhleh & Krajcik, 1994)
- Paragraph(s) describing general acid-base chemistry principles (e.g. Schmidt, 1995)
- Acceptable answers to specific open-ended probes (e.g. Ouertatani *et al*., 2007)
- Acceptable answers to multiple-choice items.
- Acceptable principles given as part of the text in the discussion section.

To ensure consistency within each of the Arrhenius and Brønsted models, I also made lists of propositional knowledge from the following sources for comparison:

- Outlines of Arrhenius and Brønsted Models by Oversby (2000a) and de Vos & Pilot (2001).
- Original historical papers, in the original or English translations (for example Arrhenius, 1903; 1912; Brønsted, 1926 and Lowry, 1923)
- Historical studies such as Bell (1969) and those in the Journal of Chemical Education such as Kolb (1978).
- IUPAC definitions for modern expert knowledge (McNaught & Wilkinson, 1997).

This propositional knowledge was typed verbatim into a Microsoft Word document, as separate statements from reports, along with the corresponding reference to its source. Since many authors reported students as having much less conceptual understanding of bases than acids, I kept statements about bases separate from those for acids so they would have equal prominence. As a result, definitions of acids and bases are not given simultaneously as in Nakhleh and Krajcik (1994). In order to categorise the statements, each item of propositional knowledge was also prefixed with key words such as ‘Base, Arrhenius’ or ‘strength, Brønsted’ which were based on the 13 broad topic headings that had been found workable (see Section 4.5.2). In this way statements could be easily sorted into categories. The consistency of propositional statements within a topic could then be evaluated, and those which suggested consensus were adopted.

Textbooks were not consulted at this stage for the reasons outlined in the literature review, namely, that content analyses around the world have shown a preponderance of mixed models in the acid-base section (see Section 2.5.3). By the same token, schoolteachers were also not consulted when deriving propositional statements because Justi and Gilbert (1999) had found that much of their content knowledge was derived from school textbooks. At this stage, I also did not consult chemistry experts because, as Furió-Más et *al*. (2005) found, due to their tacit knowledge experts may flip-flop between models without making the change overt.

The outcome of the selecting and categorising phases, was a fairly comprehensive list of possibly overlapping statements (indicating consensus), each with a reference, and sorted into broad categories according to topics. These were ready to be mapped to the student difficulties in the comparison and synthesis phases as described in the next section.

4.6.3 Using student difficulties to make missing propositional knowledge overt

With both data segments on student difficulties (Section 4.5.2) and propositional statements sorted into the same broad categories, at least one propositional statement could now be allocated to each data segment. The propositional statements chosen were given decimal numerical codes, indicating some sort of hierarchy of concepts. These were the codes used for the 'fine-sort' described in Section 4.5.3). The outcome of that sorting process was groups of data on student difficulties corresponding to particular themes of student conceptions.

On examining the propositional statements alongside similar student conceptions, I experienced a key moment in the development of the research process. I found that I could barely restrain myself from rewriting propositional statements. Only the demands of accurate reporting of research prevented me from altering my original list. I examined the intense emotions within myself and I realised I had moved into 'teacher mode'; imagining what the student needed to know in order to address or pre-empt such a difficulty. In their original from, the propositional statements could not sufficiently address the nature of the difficulty – perhaps further examples were needed, or I should clarify or extend the statement. This is exactly like the cyclical process I had adopted as a teacher, when each year I made notes, based on difficulties I had identified, of how I should modify the curriculum material for next year's students. Likewise I was sure that I could not allow these statements to remain as they were; they had to be changed. So I retained the originals, but immediately added in alterations alongside them. I realised that, in this way, I was using my PCK to make overt my more expert knowledge to address student difficulties. This is the tacit knowledge that had been missing and which needed to be engaged when deriving propositional statements.

The literature records similar processes. A first example is from a series of articles on teaching the nature of a chemical reaction. In one of these, de Vos and Verdonk (1987a) show how a definition is modified as student responses are studied, making underlying terminology clearer with each iteration. For example: "We could counter these objections by defining identical as 'not differing from each other in any way except position and motion.'" And then later: "We now declared objects to be identical if they did not *show* any difference, except in position or in motion" (p 694). These subtle changes were made in response to student feedback. As second example of this intuitive process is from Nussbaum (1998). When discussing how to identify proper instruction strategies, he advocates a first step of *cognitive analysis* of content. Such a cognitive analysis goes beyond a mere *content analysis*, or hierarchy of concepts as advocated by Herron, 1996. Rather, by using intuition and psychodidactic knowledge, which may include input from research on student misconceptions, a cognitive analysis relies on good understanding of subject matter and a natural tendency to delve into the subject matter so as to expose the deeper basic assumptions and their conceptual implications. Nussbaum thus sees a link between student conceptual difficulties and intuitively exposing the content which should be included in instruction. These two examples gave my intuitive responses to student difficulties some validity.

The new propositional statements which I had added (synthesis) were also coded, and the decimal system I had adopted proved its worth in that subdivisions could be made and new ideas incorporated into the hierarchy. An example follows to illustrate the process. I started with the statement: "Acids and bases affect the colour of indicator dyes differently" (Nakhleh & Krajcik, 1994). This was made into distinct statements for acids and bases:

- Indicators have characteristic colours in acidic solutions (code 2.1.1.2)
- Indicators have characteristic colours in basic solutions (code 3.1.1.2)

Data for difficulty P9 (Section 7.3.1.2) suggested students thought the colour was inherent in the acid so a new explicit statement was introduced:

- Indicators are substances added to solutions of acids and bases (code 6.1.1)

Then difficulty P20.1 (Section 7.4.3.3) indicated that students believed an indicator assisted with neutralization. This necessitated another statement:

- Indicators are substances that change colour at certain pH values. (code 6.1.2)

Through this process one statement has been expanded to four; such resolution of statements into finer detail was frequently warranted. A recommendation to keep propositions in the form of subject – predicate thereby linking only two concepts (Finley & Stewart, 1982; Liu, 2001) was attempted but proved to make the list pedantic. For example, propositional statement 2.1.1.7 links at least four concepts as shown by the / divisions: Acids / and some metals / react chemically / to produce hydrogen. Moreover these subdivisions made the propositional knowledge unwieldy and did not facilitate clarity for educational practitioners. Finally, the original list of propositional statements that had been derived from literature sources in the selecting phase (see Section 4.6.2) was used to verify the new expanded statements. In a few cases, it was necessary to resort to textbooks when verifying these. This verification sometimes showed discrepancies between my wording and that of experts and my statements, requiring closer examination of chemical principles, with propositional statements being subsequent reworded accordingly. At the end of this stage there was a composite list of propositional statements which reflected expert knowledge, each of which had been implicated in at least one student difficulty. The composite list could now be interpreted according to a hierarchy of chemical concepts in an educational context. This involved evaluation against criteria developed earlier (Section 4.6.1) which necessitated some further changes, as described next.

4.7 ANALYSING IMPLICATIONS OF PROPOSITIONAL KNOWLEDGE STATEMENTS

Using a full set of propositional statements implicated in any of the difficulties, this could be examined in the light of the five chosen criteria for propositional knowledge, as given in Table 4.5 (flip-out page 77). In this way I could address Research sub-question 5a*: How well do the propositional statements reflect curriculum models for acid-base chemistry?*

Three of the criteria could be applied relatively simply, through comparison. In this regard, (see Section 4.6.1) *pragmatism* (criterion 1) was evaluated through comparison with high-school curricula. As a result some more propositions were added. Then *transparency* (criterion 4) was evaluated in terms of how well the propositional knowledge reflected the paradigm of the particular models, as shown by the chemistry literature of the time and historical studies as summarised in the chemistry context (see Section 3.3). Evaluating *consensus*, to ensure the propositional knowledge was acceptable to a community of chemists, involved giving the complete list of propositional statements to two chemistry experts; both have a Ph.D. in chemistry and extensive experience in teaching introductory undergraduate courses. Differences of opinion were reconciled through discussion, and corresponding changes made to the list of propositional statements. *Parsimony* (criterion 2) was also partially evaluated by examining statements with many examples or complex phrases to decide if all were necessary for understanding. Parsimony also required other checks, as described below.

Other criteria required further analysis of the propositions, by means of concept maps. These were instituted primarily for the criterion of *consistency* (criterion 3), working from the premise that a statement that could not fit onto a map might be inconsistent with that model. These concept maps were prepared using the software *Inspirations 8.1E* (available from www.imaginginnovations.co.za) as suggested by Liu (2001). I had initially planned one map for each model, but they became unwieldy and so were split into different aspects of each model, such as examples and properties of chemical species or the nature of the acid-base reaction. Consequently the maps fall somewhere between a "macromap" summarising a course, and "micromaps" of 10 to 15 elements (Trowbridge & Wandersee, 1998, p 121). The software allowed labels for each link between concepts, on which I initially wrote words. Then as I checked off the propositional statements one by one, I substituted a code representing that proposition. In this way I identified any inconsistencies within the set of statements for a model.

Making the concept maps was helpful in three further unexpected ways. Firstly, they were essential in developing a hierarchy for the propositional statements. Codes for propositional statements were obvious once the propositions were included in the conceptual hierarchy shown by a concept map. Secondly, the concept maps alerted me to situations where essentially the same assertion was shown by two propositional statements. Such a situation showed up when the same conceptual link required codes for two statements, so then the two could be reconciled into a single statement. In this way they helped in a second way to ensure *parsimony* (criterion 2). At the end of this process the suitability of the set of propositional statements as curriculum models had been assessed. The propositional statements are given in Chapters 6, 7 and 8 together with the relevant difficulty descriptions. In addition a composite list of all the propositions arranged according to a hierarchy and the set of concept maps are given in Chapter 9. The evaluation is reported in the same chapter.

Finally, so ensure research outcomes could be interpreted within an educational context, and so add value to existing documented PCK, the last research sub-question (5b) was instituted as: *What are the implications of the propositional knowledge for teaching and learning acid-base chemistry?* Addressing this sub-question involved analysing the list of propositional statements alongside the difficulty descriptions and concept maps to identify trends in category of difficulties found in each topic, as well as showing which topics were likely to be problematic because of the hierarchy of concepts. This analysis is also shown in Chapter 9.

4.8 SUMMARY

In summary the methods adopted to analyse the student difficulties and so make overt the corresponding propositional knowledge were cyclical, iterative and involved many comparative processes. These can be summarised briefly as follows.

- Criteria were set up for the reports to include, according to the specific research question. These covered the chemistry and educational contexts as well as the type of data anticipated
- An extensive search of the literature and rigorous screening by the criteria was carried out to identify relevant publications.
- A matrix summary from these publications was made showing the scope in educational and chemistry topics investigated as well as the research method reported. Results are given in Chapter 5.
- Data segments in various formats showing evidence for difficulties and relevant propositional knowledge statements were extracted from these publications.
- These were both categorised according to the range of chemistry topics identified in the studies.
- Criteria for accepting the propositional statements were established. These cover aspects of pragmatism, parsimony, consistency, transparency and consensus.
- Each data segment for a difficulty was mapped to at least one propositional statement, with a decimal code.
- The data were sorted according to these codes, and so data concerning each specific difficulty become grouped.
- The difficulty was described, sometimes according to the propositional statements. The descriptions are reported in Chapters 6, 7 and 8.
- The classification level (on a four-level framework) for the difficulty was allocated according to the quality of the research reported in the original publications. These are reported with the corresponding difficulties in Chapters 6, 7 and 8.
- Propositional statements were sometimes increased or clarified, using researcher’s PCK, in order to address the specific difficulty. These are reported with the appropriate difficulties in Chapters 6, 7 and 8.
- The propositional statements were checked against curricula, chemistry and chemistry education publications, included on sets of concept maps and checked with expert chemists.
- The compliance of the propositional statements with the pre-determined set of criteria was evaluated. This outcome is reported in Chapter 9. Relationships within and between the set of propositional statements, concept maps and difficulty descriptions were identified to show implications for teaching and learning.

CHAPTER 5

RESULTS SHOWING SCOPE AND QUALITY OF RESEARCH ON ACID-BASE DIFFICULTIES

5.1 INTRODUCTON

This chapter presents results for the first research question: *What is the nature of research published on student difficulties with acid-base chemistry?* To answer this question it was necessary to address three sub-questions as follows. Section 5.2 addresses the first sub-question (1a) *Which reports give suitable research data on student conceptual difficulties in acid-base chemistry?* It shows results of the search for, and screening of suitable research reports on acid-base difficulties. It includes discussion on the effectiveness of various search strategies and the type of research reports that were identified as suitable for analysis. Section 5.3 considers the second sub-question (1b) *What is the scope of this research?* In describing the scope of research already conducted, it will specifically consider countries of origin and educational level of the research cohorts, research aims given in the reports and acid-base topics investigated. Section 5.4 addresses the third sub-question (1c) *What is the overall quality of this research?* It is a critique of published work where it identifies both strengths and problems prevalent in previously reported research, specifically with types of data collection instruments, design of specific probes and interpretation of student responses. The summary in Section 5.5 shows the main findings in terms of the research sub-questions with recommendations arising from the analysis concerning effective searching and research methods and reporting. The reports which were available as primary sources and were judged suitable for analysis are summarised first in Table 5.1 which is given in a flip-out format to facilitate cross-reference when these findings are discussed in greater detail later in the chapter.

Table 5.1 Analysis of research studies used for critical analysis

Author(s)	Year	Search source	Country of Study	Educational Level	Research Aims	Cohort size	Data Collection Instrument	Probes Given	Propositional Statements Given
Botton	1995	cont ERIC	UK	2j	N	n/a	CM	A	S
Bradley & Mosimege	1998	cont AcSC	RSA	3 (Tp)	A	53	MC & OE	A	S
Camacho & Good	1987	Cited	not given	2u;T; PG, Ex	N	23	I	A	0
Chiu	2005	Cited	Taiwan	e; 2j; 2s	N, X	13500	MC2	0	0
Chiu	2007	cont ERIC Google	Taiwan	e; 2j; 2s	N, X, S	>13000	MC2	0	0
Cros *et al.*	1986	cont Google	France	3	N	100	I, MC, OE	A	I
Cros *et al.*	1988	cont Google	France	3	X; L	145	pp	A	I
Demerouti *et al.*	2004	cited Google	Greece	2u	N	119	MC, MCE	A	S, G
Demircioğlu *et al.*	2004	cited ERIC	Turkey	2u	N	150	MC, OE	0	0
Demircioğlu *et al.*	2005	cont Google	Turkey	2u	L	88	I, MC	P	I
Dhindsa	2002	Cited	Brunei	3 (Tp)	N	48	OE	0	I
Drechsler & Schmidt	2005a	cont Google	Sweden	T	N	6	I	A	G
Drechsler & Schmidt	2005b	Pers	Sweden	2u	N	7	I	A	G, S
Erduran	2003	Pers	USA	2j	N	n/a	Ob	n/a	I
Furió-Más *et al.*	2007	Cont	Spain	2u	N, S	86	pp	A*	I
Hand	1989	Pers	Australia	2u	L	24	I	P	I
Hand & Treagust	1988	cited Google	Australia	2u	L	60	I, PP	0	0
Kousathana *et al.*	2005	Google	Greece	2u	N, S	119	MC, OE	A	G, S
Lambert	2005	Google	USA	2u; 2j	N, L	399	pp	A	0
Lin & Chiu	2007	cont ERIC AcSC	Taiwan	2j	N, S, L	38	MC2	A	G, S
Lin *et al.*	2004	Google	Taiwan	2j	N, S, L	38	MC2	0	0
Linke & Venz	1979	cited Google	Australia	2u	N, A	500	MC, OE	0	0

Codes for Search Sources: Cont – journal contents search; Cited – previously cited; Google – Google Scholar; ERIC database; PsycINFO database; AcSC – Academic Search Complete database; Pers – personal contact

Codes for Research Aims: L – level of understanding for a single cohort; N – nature of conceptions; P – prevalence of specific conceptions; S – source of conceptions; A – achievement on conceptual test; X - cross age comparison; L – longitudinal study over time, with or without intervention

Codes for Educational Level: e – elementary; 2j – junior secondary; 2u – upper secondary; 3 – undergraduate; 3i or 3iii – 1st or 3rd year undergraduate; Tp – pre-service teachers; T – teachers, PG, post-graduate; Ex – experts

Codes for Data Collection Instrument: A – anecdotal; I – interviews (or Ig for group interviews); Ob – observation; student generated diagram; pp – paper & pencil (no further details); OE – open-ended paper & pencil question; D – student generated diagram; MC – multiple choice question; MCE – MCQ + free explanation; MC2 – 2-tier MCQ (MC for both question & explanation); MC3 – 3-tier MCQ (MC for both question & explanation & degree of confidence) CM – concept maps (CMg = mapping exercise as group work, otherwise individual)

Codes for Probes: 0 – not given; A – all given; A* - all given in supplement available on journal website; P – some given

Codes for Propositional Statements: 0 – not given; I – inferred from report; G – general scientific principles; S – specific to probes; L – individual statements listed; C – given on concept map

Table 5.1 (continued)

Author(s)	Year	Search source	Country of Study	Educational Level	Research Aims	Cohort size	Data Collection Instrument	Probes Given	Propositional Statements Given
Nakhleh	1994	Cont Cited Google	USA	2u	N, S	14	I, D	P	I
Nakhleh & Krajcik	1993	Cont ERIC	USA	2u	L	14	Ob, I	P	0
Nakhleh & Krajcik	1994	Cont ERIC PsycINFO	USA	2u	L	15	I	n/a	L, G
Ogunniyi & Mikalsen	2004	Cont	RSA & Norway	2j	P	130; 121	pp	0	0
Ouertatani *et al.*	2007	Google	Tunisia	2u	X	86	pp: OE	A	G
Oversby	2000b	Cited ERIC	UK	2j		0	A	n/a	G
Pinarbasi	2007	Google	Turkey	3 (Tp)	N	91	pp: OE & I	P	S
Ross & Munby	1991	Cont ERIC Google	Canada	2u	N	34	I, MC	0	G, C
Schmidt	1991	Cont ERIC Google	Germany	2u	N	7500	I, MC	A	G, S
Schmidt	1995	Cont Google	Germany	2u	N	160	I, MC2, OE	A	S, G
Schmidt & Volke	2003	Cont ERIC AcSC Google	Germany	2u	S	3074	I, MCE	A	S
Sheppard	2006	Cont	USA	2u	N	16	I, D	A	I
Smith & Metz	1996	Cont Google	not given	3; PG; Ex	N	73; 22; 11	I, D	P	S
Tan *et al.*	2002	Cont	Singapore	2u	N	915	I, MCE, MC2	A	G, C
Toplis	1998	Cited ERIC	UK	2j	N	17	I, Ob	0	0
Vidyapati & Seetharamappa	1995	Cited	India	2u	N	75	I, pp	A	0
Watters & Watters	2006	Eric Google	Australia	3i; 3iii	X	10; 96	MC3	P	S
Ye & Wells	1998	Eric	USA	2u	L	81	pp	A	S
Zoller	1996	Cont ERIC	Israel	3	N	43	I, pp	P	0

Codes for Search Sources: Cont – journal contents search; Cited – previously cited; Google – Google Scholar; ERIC database; PsycINFO database; AcSC – Academic Search Complete database; Pers – personal contact

Codes for Research Aims: L – level of understanding for a single cohort; N – nature of conceptions; P – prevalence of specific conceptions; S – source of conceptions; A – achievement on conceptual test; X - cross age comparison; L – longitudinal study over time, with or without intervention

Codes for Educational Level: e – elementary; 2j – junior secondary; 2u – upper secondary; 3 – undergraduate; 3i or 3iii – 1st or 3rd year undergraduate; Tp – pre-service teachers; T – teachers, PG, post-graduate; Ex – experts

Codes for Data Collection Instrument: A – anecdotal; I – interviews (or Ig for group interviews); Ob – observation; student generated diagram; pp – paper & pencil (no further details); OE – open-ended paper & pencil question; D – student generated diagram MC – multiple-choice question; MCE – MCQ + free explanation; MC2 – 2-tier MCQ (MC for both question & explanation); MC3 – 3-tier MCQ (MC for both question & explanation & degree of confidence) CM – concept maps (CMg = mapping exercise as group work, otherwise individual)

Codes for Probes: 0 – not given; A – all given; A* - all given in supplement available on website; P – some given

Codes for Propositional Statements: 0 – not given; I – inferred from report; G – general scientific principles; S – specific to probes; L – individual statements listed; C – given on concept map

5.2 SEARCHING AND SCREENING THE REPORTS

This section addresses the first research sub-question: Which reports give suitable research data on student conceptual difficulties in acid-base chemistry? It shows results of searching for reports and screening those identified by methods described in Section 4.4. The effectiveness of search methods and the type of journal in which research was published are then also analysed.

Comprehensive search strategies identified 101 reports which already met criteria of language, publication dates and publication type (see Table 4.1, given in flip-out format on page 58). Subsequent screening of these reports, using further criteria given in Table 4.1, led to the elimination of 60 reports, to leave 41. A further publication was then included as a secondary source because the original was not available (criterion 6 on Table 4.1). This resulted in 42 reports which met all the inclusion criteria and from which some form of useful data could be extracted (see Table 5.2).

Table 5.2 Showing results of the screening process

	Reason for inclusion or exclusion	**Relevant criteria**	**Number of papers**
Included from Initial Search	meet criteria of language, publication dates & publication type possibly including student conceptions in acid-base chemistry	7, 8, 9	101
Excluded	did not include acid-base concepts	1	3
	only physiology or environmental concepts	1	2
	research on other professions	4	1
	theory of acid-base models, not student conceptions	5	11
	teaching suggestions, no research	5	20
	textbook analysis, no suitable data	6	5
	only quantitative data on conceptions	6	8
	data was already published elsewhere	6	8
	data not suitable as quotations	6	2
Further Included	publication unobtainable, cited elsewhere as secondary source	6	1
Overall number of Papers meeting criteria included in analysis		all	42

Criterion 1 excluded three reports which did not include acid-base concepts, and two which focused only on environmental issues. No reports arose in the time-frame of the search which addressed conceptual difficulties with other acid-base models (criterion 2) such as Lewis acid-base theory, although this could have been expected as ‘Lewis’ had not been used as a key-word in the search. Neither were there any reports which focused only on isolated facts rather than conceptual knowledge (criterion 3). Criterion 4 eliminated one report because the research was not in an educational setting; instead it focused on conceptions of nurses. Criterion 5 excluded a number of reports with unsuitable research aims; to be specific, five evaluated teaching programmes giving only quantitative data, another five were textbook analyses, 11 more gave outlines of aspects of acid-base models so they clarified propositional knowledge but did not include data on student conceptions, and a further 20 were teaching suggestions with no accompanying research. Seven reports duplicated data already published elsewhere; for instance Schmidt (1997) is a reinterpretation of data published earlier in Schmidt (1991; 1995) and Banerjee (1991) reported similar data to that in Schmidt (1995), but added nothing further to the research. A further two reports which gave unsuitable data (in that it was not in the form of quotations) were also eliminated through criterion 6. Finally, one report which was not available in the original was also included according to criterion 6. In summary, comprehensive searching identified 101 reports which were obtained and on scrutiny, 41 reports met all the necessary criteria, with data from one more having to be obtained from secondary sources. These 42 reports then answer Research sub-question 1a: *Which reports give suitable research data on student conceptual difficulties in acid-base chemistry?* Detailed references for these 42 publications can be found in Appendix 1 (Page 272) as well as appearing as general references. The body of work represented by the 42 reports had been published over a period of 28 years, with most of it published since 2000, confirming a recently increased awareness of student difficulties (see Section 2.4.1).

It is noteworthy that besides research studies on student conceptions; the initial search identified an appreciable amount (mostly from the Journal of Chemical Education) which clarified acid-base concepts (11 papers) and gave teaching suggestions for the topic (20 papers). I found these publications a useful resource for propositional knowledge statements (see Sections 4.6.2). They also reflect a continued effort by various practitioners to lift the quality of instruction in this topic. However, despite this wealth of information, researchers have been sufficiently concerned about authors' treatment of the topic to undertake six analyses of textbooks across the world. This suggests that authors of textbooks are not heeding this guidance along with the body of research into student conceptions (42 papers), just as Gabel (1999) indicated (see Section 2.4.4).

Perhaps textbook authors had not had access to suitable publications. Furthermore, in accordance with advice from Bennett *et al.* (2005a; 2005b) multiple search strategies had been used to identify suitable publications, which had been tedious and could perhaps be streamlined. These concerns prompted analysis of ways to identify research reports. Results of search strategies for the primary sources are given individually in Table 5.1. In addition Table 5.3 summarises data on the effectiveness of different strategies in identifying suitable primary sources of research. It can be seen from this data that only 19% of the reports were identified through more than one electronic source. Therefore a variety of strategies were indeed necessary in order to identify a wide range of reports.

Table 5.3 Effectiveness of various means of search strategies

Source of Reference	***Number of reports found**	**Percentage of 41 reports**
In 2 or more electronic sources	6	15
ERIC	13	32
PsycINFO	1	2
Google Scholar	20	49
Academic Search Complete	3	7
Academic Search Complete alone	1	2
Contents alone	4	10
Cited alone	2	5
Personal contact alone	2	5

*Some reports appeared on several databases or search engines; consequently the numbers in the table do not total 41

Data in Table 5.3 also shows that the most productive electronic searches were through Google Scholar and ERIC with, respectively, 13 and 20 of the reports being on these databases, while PsycINFO was the least helpful, having identified only one item (and that one had already been identified through ERIC). Academic Search Complete database was fruitful for only 7% of the reports, although one item (Bradley & Mosimege, 1998) would have been missed without this database. A total of eight (or nearly one fifth) of the items needed more tedious strategies, specifically journal contents searches, following up citations or using personal contacts. This indicates that these more onerous methods should not be neglected. From this analysis of search results it appears that PsycINFO database added no further value to the search for research into student conceptions in acid-base chemistry. However, is clear that in order to conduct a comprehensive review, one cannot rely on only one database, nor can one rely only on electronic strategies. The variety of search strategies needed to identify research into student conceptual difficulties in acid-base chemistry confirms the recommendation by Bennett *et al.* (2005a; 2005b) to use such diverse methods for a systematic review. Had this search been limited to databases, 20% of the reports would not have been identified. Additionally, apart from Google Scholar, these sources may not be accessible to teachers outside a university environment. This shows that searching a variety of academic databases remains a good strategy to identify suitable research but these findings are not readily available to secondary or elementary school teachers.

The nature of the journals in which research was published was also analysed (see Table5.4). This would add further insight into availability of research findings for teachers. In addition, the quality of the publications could give insight into the potential quality of the research published therein.

Table 5.4 Distribution of reports across journals

Journal	**Number of reports**
*International (or European) Journal of Science Education	9
*Journal of Research in Science Teaching	4
*@Chemistry Education: Research and Practice	3
*Research in Science Education	4
*@Journal of Chemical Education	3
*South African Journal of Chemistry	1
*@Biochemistry and Molecular Biology Education	1
#@School Science Review	5
#@Australian Journal of Education in Chemistry	1
#African Journal of Research in Science, Mathematics and Technology Education	1
#Journal of Baltic Science Education	1
#@The Chemical Educator	1
#Science & Education	1
Chemical Education International	1
Education Sciences: Theory and Practice	1
@Journal of Geoscience Education	1
Science Education International	1
Conferences: NARST 1998, NASTA 2004	2

*Appears on Science Citation Index of Institute of Scientific Information (ISI)
Not on ISI index but editorial policy includes peer-review
@ Includes educational; practitioners in target audience

Data in the table shows that more than half of the reports come from journals which appear on the Science Citation Index of the Institute of Scientific Information (marked *) while a further quarter of the reports were from journals with a peer-review editorial policy published on their websites (marked #). This suggests that much of the research should meet international research quality standards; although these reports may have been published before a journal achieved such status. Furthermore 15 reports came from journals which include educational practitioners in their target audience (marked @). This distribution shows that researchers have not only been publishing for their peers as Jenkins (2000) suggests. Instead, there has been some move towards making research outcomes available to practitioners as well.

In summary, in answer to research question 1a, extensive searches, using academic databases as well as non-electronic means, identified 101 reports which were subsequently obtained. After scrutiny, 41 reports (mostly published this century) were found to be suitable for critical analysis. They were published in journals with a target audience including both researchers and educational practitioners, with more than half of the reports appearing in internationally recognised peer reviewed journals. A secondary source, as cited by other authors, was also included.

5.3 THE SCOPE OF RESEARCH DONE

In answering the second research sub-question, concerning the scope of the research, it may be simplistic to look merely at numbers of reports published, because the quality of the research in each might vary, as might the sizes of cohorts studied. Nevertheless, it helped to understand the research distribution, variety of educational contexts studied and research aims, as shown below. Contextual data had been extracted from each research report as described in Section 4.4.2.

Accordingly, Table 5.5 gives the distribution of student cohorts studied in the suitable reports; some research was comparative between countries. The data indicates that student conceptions in acid-base chemistry come from studies in a wide range of countries. As a result there should be a wide variety of educational contexts included in the research which would be required for Level 4 difficulty descriptions (see Table 4.4, page 72).

Table 5.5 Worldwide distributions of research cohorts

Country	*Number of reports	Country	*Number of reports
Germany	3	Taiwan	4
United Kingdom	3	India	2
France	2	Brunei	1
Greece	2	Singapore	1
Sweden	2	Israel	1
Turkey	3	South Africa	2
Norway	1	Tunisia	1
Spain	1	Australia	3
USA	7		
Canada	1		

*Total numbers greater than 41 because some reports included cohorts from more than one country.

From the table it can be seen that research on students in Europe predominates, with research on Asian students having also been reported frequently. Few reports arose from research in Africa and nothing suitable was reported from South America. From this it can be seen that, despite setting a criterion (see Table 4.1) that suitable research should be reported in English, research has fortunately not been limited to Anglophone countries. Nevertheless concepts among students in developing countries have been under-researched.

As different acid-base models are taught at different stages in a student's career, it was also important to analyse the distribution of educational levels among research cohorts. The research studies were grouped according to levels familiar in South Africa where a child enters Grade 1 when 6 or 7 years old (Table 5.6).

Table 5.6 Educational levels of student cohorts

Educational level of students	**Explanation of level**	***Numbers of reports**
Elementary	Up to Grade 7, natural science students	2
Junior secondary	Grades 8 & 9, natural science students who have not yet chosen a chemistry elective	10
Senior secondary	Grades 10 to 13,	24
Tertiary	Undergraduate or honours programmes in chemistry (including pre-service teachers)	8
Teachers (including pre-service)	Teaching at any school level	4
Postgraduate	Masters or doctoral students in chemistry	2
Experts	University teaching staff	2

* Total is more than 41 because several studies compared conceptions across ages and tertiary students included pre-service teachers.

From this data it can be seen that research has included all levels of education, although not equally. The most commonly studied age group are senior secondary students. Twenty four reports on this age group indicates considerable research which could focus on conceptions of the Arrhenius and Brønsted acid-base models, as outlined in Section 3.3, for critical analysis. Possible origins of these conceptions among more junior students and their implications among tertiary students have also received some attention. Conceptions of pre-service teachers have two impacts. Firstly it indicates problems which undergraduate programmes need to address. Furthermore it indicates conceptions which may be transmitted to future students (see Section 2.3.4). Hence I have included pre-service teachers twice, and it appears these have received little attention. In brief, high school student conceptions have received considerable attention but those arising earlier or the implications of these later have been under-researched.

Research aims were analysed next, in order to understand the nature of research already carried out. These are shown individually in Table 5.1 where it can be seen that some research reports included more than one aim. In summary, 68% of the reports aimed to investigate the nature of student conceptions, with 17% of the total considering the source of these conceptions. Variation of conceptions with time among the same cohort was a stated aim for 24% of the reports. These longitudinal studies were either before and after interventions, or immediately after teaching and then some time later, so considering retention of the learning. Comparisons across ages were covered by 10% of the reports. A few reports also investigated prevalence of alternative conceptions in a cohort (2%) or achievement levels of students on conceptual questions (5%). Quantitative data from such studies was largely irrelevant in the current study. With two thirds of the research reports having a stated aim of investigating the nature of student conceptions, the body of work was then likely to be a rich source of data on the conceptions.

The particular topics in which student conceptions had been sought are summarised below in Table 5.7. Most topics included in high school acid-base curricula have been considered by the body of research. However few studies have included salts, heat of reaction, indicators, conjugate pairs or polyprotic acids. From this uneven distribution it can be expected that there would be sufficient research in some topics to achieve accurate descriptions of difficulties, while in others analysis would identify specific research gaps.

Table 5.7 Acid-base topics included in research on student conceptions

Acid-base topic	Number of reports on conceptions
Definitions	13
Neutralization	24
pH	24
Salts	4
Macroscopic properties	10
Indicators	5
Heat of reaction	3
Everyday applications	14
Formulae	9
Aqueous equilibria	11
Acid-base strength	16
Brønsted acid-base conjugates	6
Polyprotic acids	5

From all these analyses, in answer to research sub-question 1b, the scope of the research is dominated by high-school cohorts in countries across much of the world, who speak many different languages. There is a deficiency of research on students in developing countries and among teachers, and elementary or tertiary students. The nature of student conceptions has been researched for a range of acid-base topics in accordance with this being the most common research aim.

5.4 QUALITY OF THE RESEARCH

Evaluating the quality of reported findings is inherent in critical analysis (Wallace & Wray, 2006, see Section 4.5.5). Moreover, claims concerning the nature of student conceptions need to be accurate as supported by appropriate research in order for practitioners to take suitable action. For instance if false misconceptions are ‘identified’ then chosen teaching approaches could be ineffective (see Section 2.3.2), and there would be little meaningful contribution to PCK. Furthermore their use as distractors in multiple-choice items may mislead students (see Section 4.5.5.1). This section begins with a description of ‘high-quality research’ illustrated by several reports. Then problems with respect to other reports are discussed. These include problems with choice of research instruments, the design of particular instruments and interpretation of student responses. Across all three aspects there are also problems with research being underreported.

5.4.1 High Quality Research

In reviewing the 41 chosen reports I used the four-level framework (see Table 4.4, given in flip-out format on page 72) to identify publications which gave high quality research reports. Only one author (Schmidt, 1991; 1995) reported research that could meet the criteria for the student difficulties in acid-base chemistry to be classified at Level 4, based on their work alone. I describe his research process to illustrate what I consider to be a high quality research report.

Informed by suspicions gleaned from the choices students had made in Scottish chemistry examinations, Schmidt (1991) used a written open-ended questionnaire with 177 German grammar school students, followed by group interviews to investigate ideas on neutralization reactions between a weak acid and a strong base. From these results, he developed a multiple-choice instrument comprising corresponding sets of probes on the same concepts but in different chemical contexts, which he administered to 7500 school students. From the responses Schmidt could describe the conception as: “every neutralization reaction is due to end up in a neutral solution” (p 469). He established that students had been exposed to, and appeared familiar with terms relating to weak acids and bases and, moreover, had classmates who could solve the problems appropriately.

A similar procedure was followed by Schmidt in 1995. He first describes Sumfleth’s (1987) work using a connectivity test where it emerged that students “confined the concept of acid-base pairs to neutralization reactions” (p734). Then he describes a pilot study which showed "students preferred *one* of the non-conjugate acid-base pairs, namely NH_4^+/OH^-" (p734). He then explored conceptions of high school students using open-ended questions related to relevant chemical equations for three reactions. From this "it seemed that the students did not merely confuse the terms conjugate and non-conjugate. They attempted to find a matched pair of ions; one with a single positive charge, and the other with a single negative charge" (p735). Following this preliminary work two multiple-choice items, also requiring explanations, were prepared to investigate which pair of ions students would select. This instrument was administered to 160 from a selection of 4291 senior high school students and four group interviews were undertaken. The final descriptions are reported as: "they confuse non-conjugate and conjugate acid-base pairs" and "They regard positively and negatively charged ions as conjugate acid-base pairs" (p739).

The research sequences used by Schmidt, show how the description of the student conception changed: initially relating to a specific reaction then being phrased as a general student heuristic which more accurately represents student thinking. Schmidt also established neutral ground driven by students' frame of reference (Johnson & Gott, 1996) in three ways. Firstly, the Brønsted model was known to be part of the curriculum for these students, secondly students used terminology related to Brønsted model even if they arrived at the wrong conclusion, and finally students from the same class could give plausible comments using the model. In these reports, Schmidt also shows how he interpreted data triangulated from different sources in different educational and chemical contexts against a description of acceptable chemistry to arrive at stable descriptions of student difficulties. Accordingly the research met criteria for Level 4 difficulty descriptions. It is therefore astonishing that at the time of searching (May 2006 to January 2008) Schmidt (1995) did not appear on the ERIC database (see Table 5.1).

Several other projects report rigorous research but for various reasons were of limited use in the present critical analysis. In the first of these, Chiu (2005; 2007) describes an extensive project of surveying student conceptions in many chemistry topics among different age groups in Taiwan. She does not give specific details for acid-base probes but does, however, carefully document, with examples, the process by which two-tier multiple-choice items (the first choice and then the explanation for the choice) probes were designed in other topics according to Treagust's (1988; 1995) procedure. This involved preliminary open-ended written items and interviews, then piloting and validating the instrument. Although the acceptable propositional knowledge is not given explicitly, the procedure by which this had been validated through expert opinion and concept maps is also reported. The reports focus on an overall survey for the country so much of the fine-textured qualitative data had been eliminated, thereby limiting its usefulness in this review and synthesis.

Some studies showed evidence of high quality research but with limited contexts. Further research could build on these to verify the stability of the description of a student difficulty across a greater range of contexts and so enable it to be termed Established. I next discuss two early research studies which show triangulated research that was limited to only one educational context, in these cases, single cohort of students. There is a problem with the manner in which such research results are subsequently cited.

The first project (Ross & Munby, 1991) started with a multiple-choice instrument administered to a single high school class. Items had been shown to be reliable and valid from a pilot study. This was followed by two rounds of interviews that were conducted with students selected from the initial group. Data was then triangulated from the three sources to give a more complete ‘picture’ for conceptions among the single student cohort. In the second project, (Nakhleh & Krajcik, 1993; 1994; Nakhleh, 1994) collected data through two sets of interviews, pre- and post-instruction. These were combined with personal observation of the class involving protocol analysis of student verbal commentaries and discussion that occurred during laboratory exercises. The interview sequence is described, it had previously been piloted, and four experts had validated the content. Both projects therefore used several means of data collection in accordance with principles of triangulation. Interviews in the latter project were conducted on neutral ground. This aspect was shown by the interviewer asking the student: “you mentioned ... could neutralize, what does neutralize mean to you?” (Nakhleh & Krajcik, 1994, p 1080). Therefore this project also included data interpretation within students’ frame of reference. Both sets of authors describe corresponding propositional knowledge, either as a concept map (Ross & Munby, 1991) or an explicit list (Nakhleh & Krajcik, 1994) and show how they interpreted student quotations against this. From one high school class, Nakhleh and Krajcik (1994) report five clusters of conceptions showing student difficulties. Ross and Munby’s focus is more on the method of author generated concept maps. Consequently, there is no thrust to describe frequently occurring conceptions; instead, they describe the conceptions of two students in detail with general reference to the conceptions found in rest of the class. These two studies show valid and reliable probes, supported by interview quotations interpreted against scientifically acceptable knowledge which are merged to give descriptions of student conceptions. Moreover, neither pair of authors makes claims about these results being applicable beyond the study cohorts.

The problem does not lie in these research projects, but the uncritical way in which other authors have subsequently cited their results, with no reservation that they came from a single cohort, or even single students. For example, Pinarbasi (2007, p 24) writes "Nakhleh and Krajcik (1994) established that ..." with similar statements in Lin and Chiu (2007). Likewise, Dhindsa (2002, p 21) writes about Ross and Munby's work as "It has been known that students ..." Moreover, another problem arises when instead of taking this work, and building on it to be able to describe a conception more accurately (as did Schmidt) some authors use these findings without further investigation as distractors in their own multiple-choice probes. In particular, Demicioğlu *et al*. (2004; 2005) use "All acids have bubbles" (Nakhleh & Krajcik, 1994) without reporting further research. Consequently their data adds little to clarify the nature of a conception except that other students also chose these words. Other conceptions have been reported more recently through similarly triangulated quality research among single student cohorts (e.g. Demerouti *et al*., 2004; Watters & Watters, 2006; Sheppard, 2006; Furió-Más *et al*., 2007) and it remains to be seen how these will be subsequently cited. It appears that many later authors treat all reported conceptions as "established" needing no further investigation into their nature.

5.4.2 Problems with reported research

There are numerous instances where research has been either poorly designed or poorly reported, or possibly both. One report (Oversby, 2001b) included in Table 5.1 shows only anecdotal data with no research backing. There is no problem with this as it does not purport to be anything different. However where authors make claims based on research, numerous problems can be identified. Firstly, some reports do not give contextual information. For instance, neither Camacho and Good (1987) nor Smith and Metz (1996) state the country of origin of the student cohort. In another instance, Cros *et al*. (1988) do not indicate whether or not the cohort was the same cohort reported on in Cros *et al*. (1986). Moreover, problems may lie with choice of research instrument, the design of research probes and with interpretation of responses to these, as are discussed next.

5.4.2.1 Analysis of types of data collection instruments

In all the 41 selected reports some information on data collection methods was reported, which as can be seen in Table 5.1, included a variety of data collection instruments. Furthermore, in their efforts to obtain data from a variety of sources, or to investigate different chemistry contexts, nearly all the authors report some attempt towards the goal of triangulation (Lincoln & Guba, 1985; McMillan & Schumacher, 1993), even if they did not achieve full triangulation. Nearly half of the authors (n = 18) used at least two means of data collection. For example Toplis (1998) reported using both interviews and observations while Zoller, 1996 gives results from examinations answers and interviews. Some authors, however, beyond stating they used a paper and pencil instrument, gave no further details of their instruments, so their research could not be given a fair evaluation (e.g. Hand & Treagust, 1988; Ogunniyi & Mikalsen, 2004). Where authors reported only one type of instrument, all except one (Ye & Wells, 1998) included some sort of open-ended component or two-tiers of answers (MC2, MC3, MCE see Section 4.5.5.1). This diversity implies that, in line with the principles of triangulation, this analysis could fruitfully combine different investigations to give different perspectives on the same student difficulty; a necessary condition for an accurate description of the difficulty, in accordance with criteria given in Table 4.4 (in flip-out format on page 72) in order for the descriptions to be classified on the third level or above. For example, Botton (1991) (concept mapping), Nakhleh and Krajcik (1994) (interviews) and Demircioğlu *et al*. (2005) (interviews followed by paper and pencil items) would possibly combine well to show conceptions of the role of acid-base indicators.

Closer analysis of the various data collection instruments shows that interviews (I or Ig) were used to collect data in 21 (51%) studies. Pencil and paper instruments were the most popular choice as reported in 28 (68%) studies; six of which give no further details (pp). Eight (20%) reports included research with open-ended items (OE) and a further nine (22%) of the investigations included modified multiple-choice items; either with free explanations (MCE), or two-tier multiple-choice items requiring both an answer and explanation (MC2) or in one instance three-tier, which also asked for students' degree of confidence in their answers (MC3). Multiple-choice items in a conventional format of a stem with one answer and several distractors were used in ten studies (24%). Except for the one noted earlier (Ye & Wells, 1998), it is heartening that where these extremely focused instruments had been used, in all cases they had been coupled with other less focused probes: either interviews or paper and pencil items. However data from open-ended responses has not always been published in the report. In summary nearly all authors report investigating student conceptions through open-ended means, and over two thirds used paper and pencil instruments, where probes in a multiple-choice format were preferred. Only half of the projects entailed interviews, but unlike Sheppard (2006) and Furió-Más *et al*. (2007) who describe interview tasks and questions, very few authors report details of the protocol adopted in interviews. As a consequence one cannot tell if these were conducted within students' frame of reference.

Methods by which probes were designed have also not been well documented. Many authors describe the procedure by which probes were designed very briefly with few details. For instance, Linke and Venz (1979) simply report that questions had been checked by university physical science teaching staff. Cros *et al.* (1986; 1988), Ogunniyi and Mikalsen (2004), and Pinarbasi (2007) also report in such broad terms. Even worse, Demircioğlu *et al*. (2005) assert that their research probes were developed according to Treagust's (1988) method, yet they describe them as having a correct choice, a common misconception, and three "reasonable and plausible distracters" (p 43). Furthermore the only example given is a classical multiple-choice item. In their report there is no evidence of the two-tier items that characterize Treagust's procedure, so their claims about the procedure have little substance. Other authors give no sound reasons for including particular items. In this regard, Bradley and Mosimege (1998) simply based their questions on local textbooks, past examination papers, and teacher experience. These glib claims about research procedures contrast with carefully documented details of validity and reliability checks as reported by Demerouti *et al.* (2004). As a result of inadequately documented research procedures, research findings need to be used with caution.

In summary, almost all reports show that some form of open-ended instrument was included, although procedures for establishing validity and reliability of items are not well documented. This leads to doubts about the nature of particular items used in research.

5.4.2.2 Nature of research probes

The nature of research probes was analysed next. All relevant paper and pencil probes were available with 20 (49%) of the reports. For some projects these were available as an appendix (e.g. Bradley & Mosimege, 1998) or as supplemental material on the journal website (Furió-Más *et al*, 2007). Others gave these in part (e.g. Zoller, 1996), but 10 reports (24%) gave none of the probes at all (e.g. Dhindsa, 2002). Consequently, it is impossible to evaluate these. Some research probes are very simple, for example: "Give a definition of 'acid'" (Cros *et al.*, 1986, p 313) or more complex, involving over 100 words and many technical chemical and biochemical terms (Watters & Watters, 2006). Problems are evident in Bradley and Mosimege's (1998) questionnaire which lacks focus in that some items treat acids macroscopically, while others use the Brønsted model, but do not specify this. Similarly Kousathana *et al.* (2005) report on a multiple-choice item where the stem asked: "Which of the following species cannot act as an amphiprotic *substance*?" but the distractors included H_2O and the formulae for *ions*: $HCOO^-$, HCO_3^- and HS^- (my italics). In this regard, the term *substance* relates to macroscopic representations (elements, compounds, mixtures) as appropriate in the Arrhenius or operational models. By contrast, the term *species* relates to the sub-microscopic world of particles such as atoms, molecules and ions, appropriate to Brønsted model (Loeffler, 1989). Furthermore, a number of authors (e.g. Andersson, 1990; Selley, 2000) have reported that students frequently ascribe the macroscopic properties of a substance to individual atoms, molecules or ions. Thus it should be no surprise that student conceptions indicate hybrid models, when even research probes are not clear. Moreover, without clear signposts indicating appropriate models, such questions are unlikely to be within students' frame of reference as advocated by Johnson & Gott (1996). Accordingly, findings from the reports such as these cannot be taken on face value.

5.4.2.3 Data interpretation and propositional knowledge

The way in which data is interpreted also contributes to the validity of the research. Criteria given in Table 4.4 (in flip-out format on page 72) show two aspects that need be appraised in the author's interpretation of data; these are the context given in probes and the chemistry context used to interpret responses. Both should be within students' frame of reference (Johnson & Gott, 1996).

Propositional knowledge statements for the chemistry context has not been given due importance in the research reports. Some authors do not even state which acid-base model was being investigated (e.g. Linke & Venz, 1979; Demircioğlu *et al*., 2004). By contrast Ouertatani *et al.* (2007) make the context of the Arrhenius model quite clear in their title. Propositional knowledge was completely omitted in 13 reports (30%). Furthermore all but one of these purported to be investigating the nature or prevalence of student conceptions; yet they gave absolutely no indication of what they considered as scientifically acceptable. As described in Sections 2.4.6 and 4.6.1 the nature of science precludes a single unproblematic fixed body of acceptable knowledge which makes it necessary to report propositions against which student conceptions will be judged. In other reports some propositional knowledge could be inferred from a theoretical framework of general scientific principles (10 reports, 24%, e.g. Erduran, 2003) or discussion of results (9 reports, 22%, e.g. Dreschler & Schmidt, 2005a) or some statements specific to the probes (13 reports, 32%, e.g. Pinarbasi *et al.*, 2007). Only one report gave a list of individual propositional statements (Nakhleh & Krajcik, 1994) and in this there was evidence of mixed models. To elaborate, these authors claim the list represents “a synopsis of the Brønsted-Lowry model of acids and bases found in most high-school texts” (p 1078). However they devote a section to macroscopic properties such as taste, indicator colours, and titrations, which are not relevant to the model (see Section 3.3.3). Furthermore, they describe bases as proton acceptors, and describe OH^- ions as being a typical base, yet they give NaOH as an example of a base. The problem might have arisen in the textbooks from which the statements were gleaned, rather than the researchers. Nevertheless it highlights the urgent need for textbook revision according to sound propositional knowledge. Another problem occurred with scientifically unacceptable statements being given as propositional knowledge. This problem occurred with Botton (1990) where a ‘model’ concept map indicates that strong or weak acid or bases have fixed and characteristic pH values, rather than these values being variable according to the concentration of the substances in solution. The lack of these two important components of the research (qualitative data as student quotations and propositional knowledge statements against which to evaluate these) causes concern. It can result in some researchers making claims about ‘misconceptions’ with little or no evidence to back their claims (e.g. Hand & Treagust, 1988; Demircioğlu *et al.,* 2004; Ouertatani *et al*., 2007).

5.5 SUMMARY AND CONCLUSIONS

The results presented in this chapter addressed Research question 1 of the study, namely, *What is the nature of the research published on student difficulties with acid-base chemistry?* The outcomes of this work may be summarised as follows:

- A variety of databases and search engines, as well as other hand searches, were necessary to identify an initial list of 101 reports on conceptions in the topic of acid-base chemistry. Screening these reports according to predetermined criteria showed that 41 had suitable data on student conceptual difficulties with acid-base chemistry. Another report was added as a secondary source. Over half the papers were from international, peer-reviewed journals.
- The topic has been researched in a wide range of countries, predominantly in Europe and Asia; while Africa has not featured greatly and South America not at all. The dominant age group represented in the research cohorts is senior secondary school, although all age groups from elementary to post-graduates have been included.
- Two-thirds of the research reports set out to explicitly investigate the nature of student conceptions and a wide variety of acid-base topics were included.
- Little research of a high quality has been reported, and that from single cohorts has been subsequently cited without reservation.

- The need for some sort of open-ended data collection appears to have been acknowledged.
- Both probes and propositional knowledge used in research have shown examples of hybrid models, or even scientifically unacceptable statements.
- Research is frequently reported with insufficient detail. This concerns data collection instruments, their validity and reliability, qualitative data in the form of student quotations and interpretation of these against propositional knowledge, to arrive at a difficulty description.

A wide range of research represents the body of work concerning student conceptions. These have not only been published in academic research journals, but in less formal publications which include teachers in their audience. Nevertheless, the research community needs to continue finding ways to reach a target audience of practitioners and textbook authors so as to bridge this ‘gap’ between education research findings and their application in teaching practice (Anderson, 2007).

The variety of countries from which research has been drawn is encouraging, because in order to have a Level 4 or Established classification on a four-level framework (Table 4.4) the difficulty needs to be found in multiple contexts. The challenge of publishing in English has not inhibited publication of research from non-English speaking countries. Consequently a lack of research identified from Africa and South America is probably not due to research on cohorts from these continents having been published in other languages. It is therefore more likely that students from these places have simply not been the focus of much research on student conceptual difficulties in acid-base chemistry. However, as many students from countries such as South Africa do not learn science in their mother tongue, and may experience particular difficulties in this regard (Moji, 1998; Clerk & Rutherford, 2000) this is where an important research gap exists.

The dominant age-group researched has been senior secondary school. In this regard, Laugksch (2002) analysed titles of science education postgraduate degrees awarded in South Africa over a comparable time period and showed a similar distribution of ages of student cohorts –studies being dominated by research at the secondary-tertiary interface. Future research could fruitfully investigate which alternative acid-base conceptions may have their source in teaching at elementary and junior secondary school (e.g. see de Vos & Verdonk, 1987a; Stavridou & Solomonidou, 1998; Nelson, 2006). Moreover, the literature review in Chapter 2 found numerous studies identifying teachers’ contribution to student conceptual difficulties so implication of conceptual difficulties at tertiary level, particularly among pre-service teachers, is critically important.

There seems little value in attempting a remediation strategy before the nature of what you will remediate is known. Where researchers glean “misconceptions” from the literature, they would do well to evaluate these claims in terms of the underlying research on which they are based. With half of the research reports in this critique having been published in journals of international standing, and another quarter in peer-reviewed publications, it was surprising to find so many showing a low standard of research reporting. This overview and critique of research shows that most of the difficulties already reported would not be classified as Established if considered alone; this level was achieved by only one researchers’ work (Schmidt, 1991, 1995). Other studies contributed useful data, but from limited contexts. However, in Chapter 2, when providing the motivation for a more systematic review, I noted Torgerson’s (2003) comments on the value of many smaller studies. The sum of all the research will then be considered in the next three chapters, which may enable classification of some difficulties at a higher level if the accumulative insight from several studies permits this. This task is made more difficult by poorly and under-reported research. Accordingly, results from this chapter will influence interpretation of research claims is in the following three chapters.

In particular, the importance of propositional knowledge has been underestimated by many researchers. It must be acknowledged that some authors inferred they had an ideographic rather than nomothetic viewpoint, in trying to find what students thought, rather than how well their conceptions matched those accepted scientifically (e.g. Lin & Chiu, 2007). But other researchers with a clear aim of evaluating student conceptions against those which are scientifically acceptable, do not even state the acid-base model they used for a frame of reference (e.g. Bradley & Mosimege, 1998; Demircioğlu, 2005). As a result, some of their claims about student misconceptions may be misplaced – a student might simply be using a different model as his or her frame of reference, in other words simply hold an alternative conception. A further problem of authors describing hybrid or mixed models in the propositional knowledge expected from students (e.g. Nakhleh & Krajcik, 1994; Kousathana *et al*, 2005) has been identified. These issues will be addressed in the next three chapters when data on individual student difficulties are analysed alongside propositional knowledge statements.

The prevalence of deficiencies in existing research shows that the abundance of advice already published with regard to research in science education, or specifically chemistry education, (e.g. Sanders, 1993; Good, 1993a; Bunce & Robinson, 1997; de Jong *et al*. 2004; Eybe & Schmidt, 2001; Bodner, 2004) has not been heeded. In response, some guidelines can be emphasised to enhance the quality of future research (see Table 5.8).

Table 5.8 Guidelines for investigating the nature of student difficulties

1 Data should be collected through a variety of methods in order to satisfy the requirement of triangulation.

2 Research should start with exploratory studies using open-ended data sources. Similarly where suspected or emergent descriptions exist. This allows one project to build on another, avoiding ad-hoc isolated studies.

3 Details of research instrument(s) should be published, including questionnaires and interview protocols. With electronic publishing, such information can be made public as online supplements (e.g. Furió-Más *et al*., 2007).

4 Multiple-choice items are only suitable when an established description exists. These would then be useful for studies such as prevalence. They do not help to show the nature of the difficulty, unless tied to at least a second tier of explanation. Where published research is used as the base for distractors, it is important to look at the quality of the research behind the knowledge claims and their generalizability; these should not be used uncritically.

5 Both research probes and interpretation should take place within the students' frame of reference. Ambiguous words and mixed model terminology in probes can hinder identification of difficulties.

6 Propositional knowledge to indicate the researchers' frame of reference when interpreting students' responses is essential.

7 Propositional knowledge needs to be verified to avoid using mixed models.

8 Conclusions should be given with enough qualitative data to show how they arose.

9 Details of student cohorts and dates of the research are necessary.

There is nothing new in the guidelines in Table 5.8, but they are focused specifically on investigating and reporting the nature of student difficulties. Therefore they are more specific than the advice given in the publications cited above. These are based on criteria given in Table 4.4 to guide classification of descriptions and the critique in this chapter. The short list given here may serve to remind future researchers in this field.

CHAPTER 6

SYNTHESIS OF STUDENT DIFFICULTIES AND PROPOSITIONAL KNOWLEDGE REGARDING SPECIES IN ACID-BASE CHEMISTRY

6.1 INTRODUCTION

The research reported in this chapter concerns Research Question 2, namely: *What difficulties do students experience with species in acid-base chemistry?* To answer this question, I addressed the following three sub-questions:

2a. What descriptions of difficulties with acid-base species can be synthesised from the existing research data?

2b. How stable are these difficulty descriptions across different contexts?

2c. *What statements of propositional knowledge are needed to address the difficulties with species in acid-base chemistry?*

This chapter will focus only on the category of conceptual difficulties relating to the species which can be classified as acid, base, amphoteric, neutral or salt. Each difficulty description arose through analysis of the data segments obtained from the research documents meeting the criteria defined in Table 4.1. In this analysis, data segments were mapped to propositional statements, in order to formulate a description of the difficulty which was then classified on a four-level framework, according to the methods described in Section 4.5. This chapter presents four sub-categories of difficulties: namely, those which concern models of acid-base species, general acid-base definitions, everyday acid-base examples and salts and neutral solutions.

To facilitate clarity of the analysis in this chapter, an overview of the pertinent results is presented upfront in Table 6.1. This table summarizes the relevant student difficulties with a classification of each difficulty on the four-level framework. Each difficulty is followed by the propositional statements that map to the difficulty, which each have a decimal code relating to the hierarchy of concepts shown in concept maps given later in Chapter 9. Each sub-category of difficulty is then discussed, showing the evidence presented in published studies which led to the difficulty descriptions and the corresponding propositional knowledge statements. Some descriptions could be synthesized almost directly from the published reports, and in these cases the relevant analysis is described very briefly.

Table 6.1 Student difficulties with acid-base species with coded propositional statements

Difficulty Number	Difficulty Descriptions (in bold) linked to Propositional statements, with Codes	Difficulty Classification
S1.1	**Acid definitions are limited to operational definitions.** Operational and theoretical definitions are both necessary for scientific understanding. (1.1) Operational definitions indicate how a physical quantity might be recognised or measured. (1.1.1) Theoretical definitions show relationships between other concepts. (1.1.2) Acidic and basic substances have characteristic properties. (1.2) Acidic substances give acidic aqueous solutions. (2.1) Acidic solutions have a pH of less than 7 (2.1.1.1) Weakly acidic solutions taste sour. (2.1.1.3) Acidic solutions react chemically with carbonates. (2.1.1.6.2) *Interim see P19 in Chapter 7*	4
S1.2	**Base definitions are limited to operational definitions.** (1.1.1) (1.1.2) (1.2) from S1.1 Basic substances give basic aqueous solutions (3.1) *Interim, see S4* Basic solutions have a pH greater than 7 (3.1.1.1)	3+
S1.3	**Ionic compounds have no ions in solution** Ionic solids dissociate into cations and anions when they dissolve in water. (8.2.5.1) In reality, few salts dissociate completely in water. (8.2.5.1.1)	2
S2.1	**Acids are substances not particles.** Different theoretical models conceive acids as substances or as particles. (1.1.3.3) Brønsted acids are molecules or ions that can release a proton (hydrogen ion) (2.3.1.1) *Interim see S6*	4
S2.2	**Bases are substances not particles.** (1.1.3.3) from S2.1 Brønsted bases are molecules or ions that can accept a proton (hydrogen ion) (3.3.1.1) *Interim, see S6*	2
S2.3	**Examples of acids are limited to the Arrhenius model.** Brønsted acids include all Arrhenius acids (2.3.2.1) Brønsted acids include the *molecule* H_2O and *ion* NH_4^+ (2.3.2.2) *Interim, see S6* Arrhenius acids do not include water (2.2.2.2.1.1)	2
S2.4	**Examples of bases are limited to the Arrhenius model.** Arrhenius bases are limited to substances containing OH groups (3.2.2.0) Arrhenius bases include NaOH (3.2.2.1.1) Arrhenius bases do not include Brønsted bases (3.2.2.2) such as water (3.2.2.2.1) Brønsted bases include the *molecules* H_2O, NH_3 and, *ions* OH^-, $HCOO^-$, CH_3COO^-, CN^-, and S^{2-} (3.3.2.1) *Interim, see R6 in Chapter 8* Brønsted bases do not include Arrhenius bases (3.3.2.2) such as NaOH (3.3.2.2.1)	4
S2.5	**Neutralization is limited to and always occurs between compounds having H and OH in the formula** Neutralization is a process whereby acidic and basic substances react chemically to produce new substances (7.1) including water, if in aqueous solution. (7.1.2.2) CO_2 and SO_2 are acidic gases found in the atmosphere (2.1.2.2) Arrhenius bases do not include alcohols. (3.2.2.2.2)	3
S3	**One model can explain all acid-base phenomena.** Definitions vary according to different models (1.1.3) Different models are useful in different contexts (1.1.3.1)	n/a

n/a: It is not appropriate to classify the difficulty only in the acid-base context.

Difficulty Number	Difficulty Descriptions (in bold) linked to Propositional statements, with Codes	Difficulty Classification
S4	**Acid and base definitions are not distinguished** Arrhenius acids are substances that release hydrogen ions in aqueous solution. (2.2.1) Arrhenius bases are substances that release hydroxide ions in aqueous solution. (3.2.1) Brønsted model: acids are molecules or ions that can release a proton (hydrogen ion). (2.3.1.1) Brønsted model: bases are molecules or ions that can accept a proton (hydrogen ion). (3.3.1.1) Neutral substances are neither acidic nor basic. (5.1) Basic substances (or alkalis) give basic (or alkaline) solutions. (3.1)	2
S5	**Alkali is another word for base**. Arrhenius bases are substances that release hydroxide ions in aqueous solutions (3.2.1) Alkali is an alternative term for Arrhenius bases (3.2.1.1) Arrhenius bases do not include Brønsted bases (3.2.2.2) such as water (3.2.2.2.1) Brønsted bases are molecules or ions that can accept a proton (hydrogen ion) (3.3.1.1) *Interim, see S6* Brønsted bases include the *molecules* H_2O, NH_3 and, *ions* OH^-, $HCOO^-$, CH_3COO^-, CN^-, and S^{2-} (3.3.2.1) *Interim, see R6 in Chapter 8* Brønsted bases do not include Arrhenius bases (3.3.2.2)	2
S6	**Amphoteric species are neither acid nor base.** Amphoteric species are those that can behave both as an acid and a base (4.1) Amphoteric properties depend upon the context in which the species is investigated (4.1.1) In aqueous solutions, amphoteric hydroxides can form either hydrogen or hydroxide ions. (4.1.2) Amphoteric substances include $Al(OH)_3$ and $Zn(OH)_2$ (4.2.1) Arrhenius acids include HCl (2.2.2.1.1) *Interim, see R7 in Chapter 8* Arrhenius bases include NaOH, $Al(OH)_3$ and $Zn(OH)_2$ (3.2.2.1.1) Molecules or ions are classified as Brønsted acids when they release a proton (hydrogen ion) to a base. (2.3.1.1) Molecules or ions are classified as Brønsted bases when they accept a proton (hydrogen ion) from an acid (3.3.1.1) Brønsted acids: examples include the water *molecule* H_2O and the *ion* NH_4^+ (2.3.2.2) *Interim, see S6* Brønsted bases: examples include the water *molecule* H_2O, and the *ions:* OH^-, $HCOO^-$ (3.3.2.1) *Interim, see R6 in Chapter 8*	3
S7	**Acidic and basic substances are not relevant in everyday life.** Foods often contain acidic substances (2.1.2.1) Fruit, tea, milk contain acids (2.1.2.1.1) CO_2 and SO_2 are acidic gases found in the atmosphere (2.1.2.2) Basic materials are found in cleaning materials such as oven cleaner, household ammonia, household bleach; and washing soda, Na_2CO_3 (3.1.2.1) *Interim, see P3 in Chapter 7* Basic substances found in the laboratory include metal hydroxides such as limewater , $Ca(OH)_2$ (3.1.2.4) Basic substances used in cooking include ‘bicarb’ or ‘baking soda’, $NaHCO_3$ (3.1.2.3) NaCl forms a neutral aqueous solution (5.1.2)	4
S7.1	**Antacids are substances that do not react with acids.** Antacids are basic substances (3.1.2.2) used as a medicine that prevents or corrects excess acidity in the stomach (3.1.2.2.1)	3
S8	**Neutrality is not understood.** Neutral substances are neither acidic nor basic (5.1) *Interim, see P4 in Chapter 7* Neutral solutions have a pH of 7. (5.1.1)	1
S9	**Salts are not a class of compound** NaCl forms a neutral aqueous solution (5.1.2) The salt produced in neutralization reactions depends on the particular acid and base involved. (7.1.2.1.1) Acetic (ethanoic) acid and sodium hydroxide will produce sodium acetate (ethanoate). (7.1.2.1.3)	1
S10	**Neutral solutions have neither H^+(or H_3O^+) nor OH^- ions** A neutral solution is one where $[H^+] = [OH^-]$ (Arrhenius model) (5.2) or $[H_3O^+] = [OH^-]$ (Brønsted model) (5.3)	4

6.2 DIFFICULTIES WITH ACID-BASE MODELS

Different historical acid-base models were outlined in Section 3.3. This section shows difficulties which students encounter concerning differences between acid-base concepts according to three historical models (operational, Arrhenius and Brønsted) and the contexts where each model is appropriate.

6.2.1 Difficulty in accommodating more than an operational model

This difficulty can be described as three sub-difficulties with common propositional knowledge or educational implications, as discussed below.

6.2.1.1 Difficulty S1: Acid-base definitions are limited to operational definitions.

Students' tendency to limit themselves to practical experience when defining acids and bases has been shown in four studies. In these studies, students typically described acids and bases in terms of their taste (Drechsler & Schmidt, 2005b; Toplis, 1998), the pH of solutions (Cros *et al.*, 1986), or in terms of their characteristic reactions (Hand & Treagust, 1988), as in the quotation: "An acid is something which eats material away or which can burn you". While the operational model is a valid way of recognising acidic and basic substances, Cros *et al.* (1986) considered such a limited conception to be a problem. This was especially so when it persisted after a year's university tuition in chemistry during which students had been exposed to theoretical models (Cros *et al.*, 1988). Moreover, in the aforementioned studies students also tended to not distinguish *solutions* from the *substances* or from the *ions* in solution. For example Drechsler and Schmidt (2005b) report on a student who identified "the ammonium ion as sour". All these aspects map to the propositional statements below, mostly from historical sources, which focus on differentiating substances from their solutions.

- Acidic and basic substances have characteristic properties. (1.2)
- Acidic substances give acidic aqueous solutions (Arrhenius, 1887). (2.1)
- Acidic solutions have a pH of less than 7 (Lide, 2002). (2.1.1.1)
- Weakly acidic solutions taste sour (Idhe, 1970). (2.1.1.3)
- Acidic solutions react chemically with carbonates. (2.1.1.6.2)
- Basic substances give basic aqueous solutions (Arrhenius, 1887) (3.1)
- Basic solutions have a pH greater than 7. (Lide, 2002) (3.1.1.1)

The propositional knowledge shown above, which apparently missing for the students in the studies as mentioned above, has a common thread which in turn suggests a description of the difficulty: *Acids and bases are defined according to the properties of acidic and basic* *solutions.* This difficulty description was then examined in the light of Galili and Lehavi's (2006) work on definitions in relation to understanding the nature of science. The conceptions reported above suggest that students had focused on operational definitions whereas the authors above had seemingly expected more theoretical definitions. Accordingly, the difficulty can map to further propositional knowledge:

- Operational and theoretical definitions are both necessary for scientific understanding (1.1)
- Operational definitions indicate how a physical quantity might be recognized or measured. (1.1.1)
- Theoretical definitions show relationships between concepts (1.1.2)

Consequently, through a second iteration of mapping the propositional statements back to the difficulty, its description can be honed to: Definitions of acids and bases are limited to operational definitions. However, in order to reflect the differing number of contexts investigated (in this case fewer for bases), the difficulty has been separated into two sub-difficulty descriptions, as follow:

Difficulty S1.1: Definitions of acids are limited to operational definitions. Level 4

Difficulty S1.2: Definitions of bases are limited to operational definitions. Level 3+

Another way in which the difficulty manifests itself is described below.

6.2.1.2 Sub-difficulty S1.3 Ionic compounds have no ions in solution

Furió-Más, *et al.* (2007) reported that students apply the following representation by heart without thought of dissociation: acid + base → salt + water. This contention is borne out by an earlier study where tertiary students were asked to create their own particle representations of certain chemical processes. From this research Smith and Metz (1996) report that some students' drawings did not show dissociation of ionic species, instead they represented the dissolved NaOH as molecules. If students do not have a mental model of solutions containing ions, it will be difficult for them to apply the Arrhenius model of ions in solution so they will be limited to using an operational model. The difficulty as described by Smith and Metz (1996) comes from one data source and has not been verified in other contexts and so is classified as Emergent or Level 2. These students may lack knowledge of ionic bonding and need a mental model of dissociation, but in the acid-base context the difficulty maps to the following propositional statement which are suggested by Smith and Metz' work:

- Ionic solids dissociate into cations and anions when they dissolve in water. (8.2.5.1)

This might be too simplistic for tertiary students, who should also understand,

- In reality, few salts dissociate completely in water. (Hawkes, 1996a) (8.2.5.1.1)

Even when students have progressed beyond this difficulty, to a theoretical conception of acids and bases, there may be further difficulties as shown by the cluster described next.

6.2.2 Difficulties with the Brønsted model

Five sub-difficulties, all with similar implications in terms of students understanding and propositional knowledge are discussed in this section.

6.2.2.1 Difficulty S2: Acids and bases are substances not particles

Student conceptions of acids and bases may have advanced to the theoretical Arrhenius model of substances in aqueous solution, but in some cases students do not yet accommodate the Brønsted model of particles as proton donors or acceptors, despite having studied the later model at senior secondary or tertiary level. For example Kousathana *et al*. (2005) reported that students who were asked to chose an option that: "is not a Brønsted-Lowry acid" from a selection of four species still justified their choice by reference instead to the Arrhenius model. Similar ideas are reported from Cros *et al*. (1986). More specifically, the student difficulty of distinguishing the essential attributes of the Brønsted model (that it concerns particles such as molecules or ions rather than substances, see Section 3.3.3.1) was identified among students (Sumfleth, 1987) and teachers (Drechsler & Schmidt, 2005a). This essential attribute of the model is indicated in the propositional knowledge statements given below.

- Different theoretical models conceive acids and bases as substances or as particles (1.1.3.3)
- Brønsted acids are molecules or ions that can release a proton (hydrogen ion) (2.3.1.1)
- Brønsted bases are molecules or ions that can accept a proton (hydrogen ion). (3.3.1.1)

As in the previous difficulty, less research has been reported on the student conception for bases (only Drechsler & Schmidt, 2005b) than for acids. Accordingly, the difficulties have been separated so that classifications levels can indicate this disparity, as follow:

Difficulty S2.1: Acids are substances not particles Level 4

Difficulty S2.2: Bases are substances not particles Level 2

The Difficulty S2 can also show itself in other ways, which are discussed as sub-difficulties in the following two sections.

6.2.2.2 Sub-difficulties of S2: Examples of acids and bases are limited to the Arrhenius model

Some students think that only compounds with OH groups are bases and in this way limit themselves to Arrhenius bases. Similarly they also do not recognise Brønsted acids that are not also Arrhenius acids. Table 6.2 below shows a summary of the relevant research for this sub-difficulty. In this research, some probes were open ended (Cros *et al.*, 1986), others asked students to classify examples as acids, bases or neutral species (Furió-Más *et al.*, 2007; Ouertatani *et al.*, 2007) or probes were in a multiple-choice format along the lines of: *Which of the following is not a Brønsted acid or Brønsted base* (Kousathana *et al.*, 2005).

Table 6.2 The formulae for species not recognised as Brønsted bases or acids by students

	Formula investigated	Educational level of students	Country of Cohort	Authors
Bases	NH_3	Senior secondary	Greece	Kousathana *et al.* (2005)
	NH_3	Senior secondary	Spain	Furió-Más *et al.* (2007)
	NH_3	Senior secondary	Tunisia	Ouertatani *et al.* (2007)
	CN^-	Senior secondary	Greece	Kousathana *et al.* (2005)
	S^{2-}	Senior secondary	Tunisia	Ouertatani *et al.* (2007)
	CH_3COO^-	Tertiary	France	Cros *et al.* (1986)
	CH_3COO^-	Senior secondary	Tunisia	Ouertatani *et al.* (2007)
	$HCOO^-$	Senior secondary	Greece	Kousathana *et al.* (2005)
Acid	NH_4^+	Senior secondary	Greece	Kousathana *et al.* (2005)

The research summarised in the table was conducted among many cohorts of senior students in a variety of countries to give a coherent picture of the student difficulty which can be described directly from the data as given in the section heading above. The research has covered a wide variety of Brønsted base species, including both molecules such as ammonia, NH_3, and ions such as CN^-. Furthermore similar conclusions regarding bases are reported from other research (Schmidt & Volke, 2003; Drechsler & Schmidt, 2005b). However, only one Brønsted acid was included (ammonium ion, NH_4^+) and this research concerned only one student cohort. Consequently, for the purpose of classification the difficulty is separated into two sub-difficulties, as follows:

Sub-difficulty S2.3 Examples of acids are limited to the Arrhenius model. Level 2

Sub-difficulty S2.4 Examples of bases are limited to the Arrhenius model. Level 4

The research described above shows that students have limited knowledge of Brønsted bases, and also need examples of Brønsted acids that are not also Arrhenius acids. Research by Drechsler and Schmidt (2005b) suggests that the student conception could be directly caused by limited examples introduced during instruction. To address the problem, teachers need to be aware that propositional knowledge should include a variety of examples to indicate both the extent of the Brønsted model and where it differs from the Arrhenius model. I attempted to take cognisance of these aspects in the three propositional statements below.

- Arrhenius bases are limited to substances containing OH groups. (3.2.2.0)
- Brønsted bases include *molecule* NH_3, and *ions* $HCOO^-$, CH_3COO^-, CN^- and S^{2-} (3.3.2.1)
- Brønsted acids include the *ion* NH_4^+ (2.3.2.2)

Discussion of individual substances which pose particular problems for students follows. These substances represent specific contexts for Difficulties S2 and accordingly, they are not considered to be separate difficulties.

6.2.2.3 Specific contexts of Difficulty S2

Familiarity with water makes it especially difficult for students to accommodate into the more abstract Brønsted model. Analysis of examination board answers showed that students avoided options where water was described as a base, or where it acted as a proton acceptor (Drechsler & Schmidt, 2005a) which is confirmed by Kousathana *et al.* (2005). The quotation: “I can't imagine drinking an acid but you drink water” (Drechsler & Schmidt, 2005b) suggests that students have the substance water in mind, rather than water molecules. Schmidt and Volke (2003) report similarly concerning water as a base. Consequently education practitioners need to be especially careful to clarify that the Brønsted model refers to water molecules, as shown by the propositional knowledge given below.

The second substance presenting particular difficulty is sodium hydroxide, a prototypic Arrhenius base. In this regard, Drechsler and Schmidt (2005b) quote a student who claimed to be using the Brønsted model but said: “HCl is the acid and NaOH is the base”. For both these substances, students were superimposing their limited conception of acids or bases as substances onto the Brønsted model. Teachers (and textbook authors) need to be particularly aware of the difficulties encountered with these substances. Accordingly, the propositional statements below are modified from those given earlier. They now address the specific contexts of the difficulty and clarify the boundaries of the models as recommended by Herron (1996), through a range of both examples and non-examples.

- Arrhenius acids do not include water (2.2.2.2.1.1)
- Brønsted acids include the *molecule* H_2O and *ion* NH_4^+ (2.3.2.2)
- Arrhenius bases include sodium hydroxide, NaOH. (3.2.2.1.1)
- Brønsted bases include the *molecules* H_2O, NH_3, and *ions* OH^-, $HCOO^-$, CH_3COO^-, CN^- and S^{2-} (3.3.2.1)

- Brønsted base: examples do not include Arrhenius bases (3.3.2.2) such as NaOH (3.3.2.2.1)

The next section shows how limited conception of acids and bases impacts on student conceptions of their reactions.

6.2.2.4 Sub-Difficulty S2.5: Neutralization is limited to and always occurs between compounds having H and OH in the formula

From the Difficulty S2, it follows that students would have a limited conception of species involved in acid-base reactions, as shown by the sub-difficulty described above. Evidence for this sub-difficulty, reported by Furió-Más *et al.* (2007), is summarised in Table 6.3 below. Ouertatani *et al.* (2007) also reported similar observations.

Table 6.3 Some of the reaction equations investigated by Furió-Más *et al.* (2007)

	Reaction equation investigated	Classification by students	Incidence	Acceptable classification
1	$SiO_2 + CaO \longrightarrow CaSiO_3$	Not neutralization	11	Neutralization in Operational model or Lewis model (Theoretical framework)
2	$HCl + CH_3OH \longrightarrow CH_3Cl + H_2O$	Neutralization	91	Nucleophilic substitution (Morrison & Boyd, 1966)
3	$NH_3 + CH_3OH \longrightarrow CH_3NH_2 + H_2O$	Neutralization	97	Nucleophilic substitution (Morrison & Boyd, 1966)

The first reaction between silicon dioxide and calcium oxide shown by equation 1 in the table above could fit the operational model for a non-aqueous system or even a Lewis acid-base reaction (see Section 3.3.4), but was not recognised as such by some students. The reaction between hydrogen chloride and methanol (equation 2) and that between ammonia and methanol (equation 3) were both overwhelmingly identified as neutralization, which the authors consider incorrect. Morrison & Boyd (1966) confirm that the reactions shown as (2) and (3) above are nucleophilic substitution of alcohols rather than neutralization. Consequently, it appears that not only do students limit their idea of neutralization reactions to species with H atoms and OH groups but also they consider all reactions shown in this format as neutralization, that is, an acid-base reaction. Accordingly, the description for the difficulty: *Neutralization is shown by reactants with H and OH in the formulae* is classified at Level 3 because it has been identified through two investigations using a variety of open-ended methods and different chemical contexts. The corresponding propositional knowledge shows that the operational model can accommodate non-aqueous systems. Students need to integrate the propositional knowledge below, which includes a modified statement 3.1.2.4 to account for calcium oxide.

- Neutralization is a process whereby acidic substances and basic substances react chemically to produce new substances (7.1) including water, if in aqueous solution. (7.1.2.2)

- CO_2 and SO_2 are acidic gases found in the atmosphere. (2.1.2.2)
- Basic substances found in the laboratory include metal oxides or hydroxides such as limewater $Ca(OH)_2$ (3.1.2.4)
- Acidic substances and basic oxides or hydroxides react chemically but produce no gases except water vapour. (2.1.1.6.1)
- Arrhenius bases do not include alcohols. (3.2.2.2.2)

6.2.3 Difficulty S3: One model can explain all acid-base phenomena.

Much has been published concerning students difficulty in accommodating multiple models, which are suitable for use in different contexts (for example Glynn, 1991; Justi & Gilbert, 1999; 2002b). This has also been shown in the specific context of acid-base chemistry with the following quote from a senior secondary student: “It would have been better to learn Brønsted from the beginning. It gets messy to change models when you have already learned it one way” (Drechsler & Schmidt, 2005b). Based on such statements, these authors conclude: “Students did not realise that several models are available to explain acid-base reactions”. In this regard, criterion 3 given in table 4.3 requires that propositional statements define the context and limitations of each model. Accordingly, propositional statements should make explicit the need for different models (which were outlined in Section 3.3) as given below.

- Definitions vary according to different models. (1.1.3)
- Different models are useful in different contexts. (1.1.3.1)

The propositional statements suggest the following description of the difficulty: *One model can explain all acid-base phenomena.* As mentioned above, this is part of a larger problem in which students have difficulty accommodating the need for multiple models into their schema and understanding the nature of models. This difficulty is found in wider contexts than acids and so it is inappropriate to classify it only in the context of acid-base chemistry.

6.3 DIFFICULTIES WITH GENERAL DEFINITIONS

This section concerns student difficulties with distinguishing definitions of acid and base, and with other definitions in the topic.

6.3.1 Difficulty S4: Acid and base definitions are not distinguished

Some students, even in senior secondary classes, interchange the definitions for acids and bases, as reported in numerous studies below (see Table 6.4).

Table 6.4 Summary of research on interchanged acid-base definitions

Reported student conception	Educational level of students	Incidence	Author(s)
Acid-base definitions interchanged	Senior secondary	7%	Linke & Venz (1979)
Same definition given for both acid & base	Senior secondary	4%	Linke & Venz (1979)
Acid-base definitions interchanged	Senior secondary	Not available	Vidyapati & Seetharamappa (1995)
OH^- ions are found in acids	Senior secondary high achiever	Not applicable	Ross & Munby (1991)
Acids can be alkaline or neutral	Junior secondary	Not available	Toplis (1996)
Acid is an acceptor of hydrogen ions.	Senior secondary	10%	Ouertatani *et al.* (2007)
Acid is a donor of hydroxide ions.	Senior secondary	10%	Ouertatani *et al.* (2007)
Base is an acceptor of hydroxide ions.	Senior secondary	20%	Ouertatani *et al.* (2007)

The relatively small prevalences (4% and 7%) reported by Linke and Venz (1979) above could suggest that these might simply be mistakes, which are easily corrected, rather than genuine conceptual difficulties (Abimbola, 1988). However the higher incidences reported by Ouertatani *et al.* (2007), particularly with the definition of a base, indicates otherwise. So this is evidently not a trivial difficulty, and it needs further investigation. Towards this end, questions such as the follow need addressing: “What links do students need in order to conceptualize these definitions?”; “Why are they unable to form links between the definitions and other knowledge?”; and, “What aspect of the definitions are students confusing – the hydrogen and hydroxide ions, or the words *acceptor* and *donor*, or perhaps superimposing the acceptor / donor aspects of the Brønsted model onto the Arrhenius model?” There could even be confusion with the Lewis model if students have heard of acids as electron pair acceptors and bases as electron pair donors. The description of the difficulty arising from the author’s descriptions is still exceptionally vague, not indicating its essence at all. As a result I can only classify it is as Emergent – Level 2 – despite its having been reported in five educational contexts. Further research should probe which conceptual links are missing for these students but, in the interim, propositional knowledge should include at least the definitions for both acid and base according to both theoretical models, as follow:

- Arrhenius acids are substances that release hydrogen ions in aqueous solution. (2.2.1)
- Arrhenius bases are substances that release hydroxide ions in aqueous solution. (3.2.1)
- Brønsted model: acids are molecules or ions that can release a proton (hydrogen ion). (2.3.1.1)
- Brønsted model: bases are molecules or ions that can accept a proton (hydrogen ion). (3.3.1.1)

The student conception given by Toplis (1996) requires mapping to further propositional statements (3.1 now modified to include alkalis) that concern operational knowledge of both neutral and alkaline solutions.

- Neutral substances are neither acidic nor basic. (5.1)
- Basic substances (or alkalis) give basic (or alkaline) solutions. (3.1)

6.3.2 Difficulty S5: Alkali is another word for base

Two research studies show a conception indicating that students transfer a concept from the Arrhenius model inappropriately onto the Brønsted model. A student interviewed in Schmidt and Volke's (2003) study responded: "Water as an alkali is difficult to conceive" and Toplis (1998) reported similarly. The difficulty description given above arises directly from this data. The term alkali applies in the chemistry context of substances and so has no place in the Brønsted model (see Section 3.3.3). Consequently, this difficulty maps in one step to the following propositional statements, which go beyond merely defining a base according to the two theoretical models, in an attempt to show the boundaries between two conceptions of bases.

- Arrhenius model: bases are substances that release hydroxide ions in aqueous solution. (3.2.1)
- Alkali is an alternative term for Arrhenius bases. (3.2.1.1)
- Arrhenius bases do not include Brønsted bases (3.3.2.2) such as water. (3.2.2.2.1)
- Brønsted bases are molecules or ions that can accept a proton (hydrogen ion) (3.3.1.1)
- Brønsted bases include the *molecules* H_2O, NH_3 and, *ions* OH^-, $HCOO^-$, CH_3COO^-, CN^-, and S^{2-} (3.3.2.1)
- Brønsted bases do not include Arrhenius bases (3.3.2.2)

Few research details are given by Toplis and Schmidt and Volke did not report pursuing the difficulty beyond interviews with a few students. Consequently the difficulty, *alkali is another word for base* can be classified only as Level 2, or Emergent. Other authors have not built on this work and so further research is needed to verify that the description is stable across other contexts. Furthermore, the research reported on this difficulty does not indicate whether the teachers concerned used mixed models and so caused the difficulty or whether the students themselves were unable to differentiate two models they had been taught. Accordingly, while this propositional knowledge may not be sufficient to address the difficulty, it represents a minimum of scientifically correct propositions that are necessary.

6.3.3 Difficulty S6: Amphoteric species are neither acid nor base.

The student difficulty with amphoteric species goes beyond merely not knowing the concept label or definition (Bradley & Mosimege, 1998) or not recognising aluminium or zinc hydroxides as possible proton donors (Furió-Más *et al.*, 2007). Kousathana *et al.* (2005) showed that two multiple-choice items with small differences elicited different student responses. The first question asked which species could not act as an amphiprotic (that is amphoteric) substance and the second asked which species could not act as both an acid and a base in the Brønsted model. In both cases the answer ($HCOO^-$) and the distractors (H_2O, HCO_3^- and HS^-) were the same. Although for both items students seemed to prefer to give no answer rather than choose any of the options, performance was much better with the term amphiprotic, 70% against 49%. The authors speculate that students had created a new class of substances, so that substances are classified as acids, bases or amphoteric substances; in other words the three are mutually exclusive. This conception can be mapped to the propositional knowledge given in the IUPAC 'Gold book' (McNaught & Wilkinson, 1997), namely:

- Amphoteric species are those that can behave both as an acid and a base. (4.1)
- Amphoteric properties depend upon the context in which the species is investigated. (4.1.1)

The evidence of student difficulties from Kousathana *et al.* (2005) together with the corresponding propositional knowledge suggests that students do not understand another critical aspect of the Brønsted model; specifically, that acids and bases are so classified in relative rather than absolute terms, according to the context of the reaction (see Section 3.3.3). In response, the Brønsted definitions already given as propositional statements for Difficulties S2.1, S2.2, S4 and S5 were modified to emphasise this aspect, and emphasising that there must be a suitable acceptor for, or donor of the proton present. Furthermore, bearing in mind the students' mutually exclusive conception it was judged more appropriate to give lists of examples of Brønsted acids and bases, which included some items common to both, rather than a separate list of amphoteric species which might be seen as separate from acids and bases. Consequently, two types of propositional knowledge were involved in this difficulty; firstly explicit definitions of acid and bases and secondly lists of examples for acids and bases expanded so as to include the examples introduced in the research on this difficulty. Accordingly, the difficulty mapped to the following propositional statements.

- Examples of amphoteric substances include $Al(OH)_3$ and $Zn(OH)_2$ (4.2.1)
- In aqueous solution, amphoteric hydroxides can form either hydrogen or hydroxide ions. (4.1.2)
- Molecules or ions are classified as Brønsted acids when they release a proton (hydrogen ion) to a base. (2.3.1.1)
- Molecules or ions are classified as Brønsted bases when they accept a proton (hydrogen ion) from an acid. (3.3.1.1)
- $Al(OH)_3$ and $Zn(OH)_2$ may act as acids in certain reactions. (2.3.2.2)
- Arrhenius bases: examples include NaOH, $Al(OH)_3$ and $Zn(OH)_2$ (3.2.2.1.1)
- Brønsted acids: examples include the *molecule* H_2O and *ions*: NH_4^+, HCO_3^- and HS^- (2.3.2.2)
- Brønsted bases: examples include the *molecule* H_2O and *ions*: OH^-, CH_3COO^-, $HCOO^-$, CN^-, S^{2-}, HCO_3^-, HS^- (3.3.2.1)

Reversing these propositional statements suggests the following description of the difficulty: *Species can be classified as acids or bases or amphoteric.* However, when mapped back to the difficulty data, it was clear that this description did not show the mutually exclusive nature of the conception identified by Kousathana *et al.* (2005). Accordingly, the description was further modified to*: Amphoteric species are neither acid nor base.* The classification is at Level 3 because it has only been studied in only a limited way, one educational context. Further research should use open-ended methods to verify whether students do see these three categories as mutually exclusive.

As a teaching exercise, it would be useful for students to fill in examples of acids and bases onto a diagram such as in Figure 6.1 given below. Some species may only be able to act as acids (e.g. HCl or NH_4^+), some might only be able to act as bases (e.g. CO_3^{2-} and $HCOO^-$), while others could fall into the common classification and be termed amphoteric.

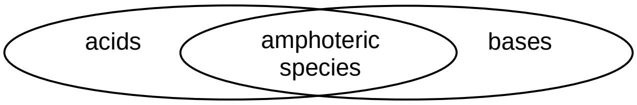

Figure 6.1 The relationship between species classified as acid, base or amphoteric

6.4 DIFFICULTIES WITH EVERYDAY ACID-BASE EXAMPLES

The macroscopic tangible experience of chemistry is not as simple as it appears. The evidence discussed in this section shows that students have difficulties even with the most directly experienced operational acid-base model.

6.4.1 Difficulty S7: Acidic and basic substances are not relevant in everyday life.

Students' knowledge of everyday examples of acidic and basic substances has been investigated across all ages of secondary school students (see Table 6.5 below). The data shows that basic substances encountered commonly in a school laboratory (such as limewater) are sometimes incorrectly classified as acidic, and even senior students are unaware that CO_2 and SO_2 are acidic gases (with high incidences) and that many foodstuffs are acidic.

Table 6.5 Student conceptions of everyday acid-base examples

Substance or material	Classified by students as	Instead of	Incidence	Educational level of students	Reported by
Limewater, [metal] hydroxide & bicarbonate	acids	basic	N/A	Junior secondary	Toplis (1998)
CO_2	neutral	acidic	27 & 41%	Senior secondary	Ouertatani *et al.* (2007)
SO_2	not acidic	acidic	73%	Senior secondary	Furió-Más *et al.* (2007)
Foods (including fruit), tea and coffee	basic	acidic	N/A	Senior secondary	Ross & Munby (1991)
Milk	basic	acidic	N/A	Senior secondary	Ross & Munby (1991) Nakhleh & Krajcik (1994)
NaCl & baking powder	bases	Neutral & mixture of acidic and basic solids	N/A	Senior secondary	Nakhleh & Krajcik (1994)

N/A: the incidence of the conception was not applicable in the research project

One research publication in the table above was confusing (Ross & Munby, 1991). These authors report (p 15) that a student "*correctly* classified ammonia and bleach as acidic" (my italics) but later (p 21) they state that the same conception represents a *misconception*. Although ammonia is not accepted as an Arrhenius base (and this is a point where the model breaks down, see Section 3.3.2.2. of the Theoretical Framework) it is a good example of a Brønsted base (e.g. Kousathana *et al*., 2005). Furthermore, Brady and Holum (1993, p 892) note that typical household 'liquid bleach' has a pH of 11 (so it is clearly basic) in order to favour the formation of the stable $OCl^-(aq)$ ion. I can only presume that the initial research claim was erroneously reported and the student had *incorrectly* identified these two substances as acidic. Researchers have also noted that students show less knowledge about bases than about acids (e.g. Nakhleh & Krajcik, 1994) and this is shown in the limited range of examples which students give for bases (Ross & Munby, 1991; Cros *et al.*, 1986; Ouertatani *et al.*, 2007). To address the paucity of everyday examples (particularly for basic materials) and the erroneous examples, a range of these is included in the following propositional knowledge, which students need in their conceptual structure.

- Foods often contain acidic substances (2.1.2.1)
- Fruit, tea and milk contain acids (2.1.2.1.1)
- CO_2 and SO_2 are acidic substances found in the atmosphere. (2.1.2.2)
- Basic substances are found in cleaning materials such as oven cleaner, household ammonia and household bleach. (3.1.2.1)
- Basic substances found in the laboratory include metal hydroxides such as limewater, $Ca(OH)_2$ (3.1.2.4)
- Basic substances used in cooking include ‘bicarb’ or ‘baking soda’, $NaHCO_3$ (3.1.2.3)
- NaCl forms a neutral aqueous solution (5.1.2)

The evidence in the table above indicates that students do not have or do not integrate empirical knowledge of acid-base behaviour. Furió-Más *et al*. (2007) claim this means they have little understanding of the importance of acids and bases in everyday life, whether at home or in the laboratory. In this regard, Cros *et al*. (1986) note: “the link between everyday life and scientific ideas has not been properly established”. Both Furió-Más *et al.* (2007) and Pinarbasi *et al*. (2007) interpret Cros *et al*.’s (1986) work as showing that students “do not connect their knowledge with everyday phenomena”. The difficulty description arises from these interpretations, together with the propositional statements above, and is given as: *acidic and basic substances are not relevant in everyday life*. The evidence for the conception comes from multiple contexts and so the difficulty is classified at Level 4, Established.

6.4.2 Sub-difficulty S7.1 Antacids are substances that do not react with acids

The specific everyday example of bases in antacid medicines has been investigated in two independent research projects which identify the same difficulty with the term antacid (Ross & Munby, 1991; Vidyapati & Seetharamappa, 1995). The difficulty description given above comes almost exactly from these sources without further analysis. The classification of Level 3 or as Partially Established arises from the three sources of data used to verify the conceptual link on an individual student’s profile (Ross & Munby, 1991) with confirmation in another educational context from two rounds of interviews and a questionnaire given to a large group of students (Vidyapati & Seetharamappa, 1995). The difficulty needs to be confirmed in other contexts but I do not anticipate the description changing substantially from that given above. The difficulty could be founded in students' lack of experience and consequent superficial reasoning with language. With similar aged students, I taught the chemistry of acids and bases in an everyday context through an investigation to compare the efficacy of different brands of antacids. This involved studying the reactions of the active ingredients with hydrochloric acid and using titrations to provide quantitative data. At the start of the unit, I was astonished to find that few of the students knew what I meant by an antacid; few of them had experienced indigestion, or had needed to use these remedies. Following from the research findings above and my teaching experience, and while focusing the propositional knowledge on chemistry rather than human physiology, I suggest the propositional statements below. They are based on a simple dictionary explanation (Oxford, 2002) and propositional statements from Vidyapati and Seetharamappa (1995).

- Antacids are basic substances (3.1.2.2) used as medicine that prevents or corrects acidity in the stomach. (3.1.2.2.1)

6.5 DIFFICULTIES WITH NEUTRAL SOLUTIONS AND SALTS

The species involved in acid-base chemistry include not only acids and bases, but also salts and neutral substances. In an operational model salts are formed in acid-base reactions, while neutral species do not display acidic or basic properties. In this section, two categories of difficulties with respect to these two chemical classes are discussed. These are difficulties firstly with the macroscopic operational recognition of the classes and secondly explanations at sub-microscopic level for the behaviour of neutral solutions and salts.

6.5.1 Macroscopic aspects of neutral solutions and salts

6.5.1.1 Difficulty S8: Neutrality is not understood.

A difficulty with the concept of neutral substances in the acid-base context has been reported with unanticipated data from two studies. These are a 12th Grade chemistry student who could not name a single substance with pH of 7 (Ross & Munby, 1991) and a junior secondary student who states: "acids can be alkaline or neutral" (Toplis, 1998). These two instances are enough to suspect a Level 1 difficulty, which at this stage can only be described very vaguely as: *neutrality is not understood.* An important consequence of not having a firm understanding of neutrality in the context of acids and bases is found in a study falling outside the criteria for this review (See Table 4.1 in Chapter 4). From this study, Wilkes and Batts (1996) report the conceptions of professional nurses such as "neutral is pH 5.5". With the importance of acid-base balance in human physiology, this belief could have tragic consequences. The following propositional knowledge statements correspond to this difficulty:

- Neutral substances and solutions are neither acidic nor basic (5.1)
- Neutral solutions have a pH of 7. (5.1.1)

6.5.1.2 Difficulty S9 Salts are not a class of compounds

Two research reports indicate students do not recognise salts as a class of compounds. Firstly, as mentioned earlier (Table 6.5 in Section 6.4.1), table salt, NaCl, was given as an example of a base (Nakhleh & Krajcik, 1994). Secondly, Lin and Chiu (2007) report on a student who thought that table salt was produced when any acid was mixed with sodium hydroxide, even acetic acid. Both these reports indicate that the data arose unexpectedly during the research, and the difficulty description as given above is very vague. Consequently, it is classified as suspected, or Level 1. Further research would discover whether such ideas are idiosyncratic or more pervasive among students. In the interim, I suggest the following propositional knowledge is pertinent:

- NaCl forms a neutral aqueous solution. (5.1.2)
- The salt produced in neutralization reactions depends on the particular acid and base involved. (7.1.1.2.1)
- Acetic (ethanoic) acid and sodium hydroxide will produce sodium acetate (ethanoate). (7.1.2.1.3)

6.5.2 Sub-microscopic aspects of neutral solutions

6.5.2.1 Difficulty S10: Neutral solutions have neither H^+ (or H_3O^+) nor OH^- ions.

According to some students, water does not contain ions. Concerning this conception, one extensive research project (Schmidt, 1991, see Section 5.4.1) has established the difficulty described above at Level 4 and also given the following propositional knowledge:

- A neutral solution is one where $[H^+] = [OH^-]$ (Arrhenius model) (5.2) or $[H_3O^+] = [OH^-]$ (Brønsted model) (5.3)

Two other projects (Dhindsa, 2007; Lin & Chiu, 2007) give further evidence of the conception, but add nothing further to the description. This student conception has a number of consequences for (mis)understanding aqueous equilibria, so could hinder student understanding of pH and hydrolysis of anions and cations.

6.6 INAPPROPRIATELY REPORTED DIFFICULTIES

Some researchers have reported as misconceptions, student ideas which are possibly acceptable within a framework of an alternative acid-base model. Discussion of four reported misconceptions follows.

In the first case, an apparent anomaly arises from the propositional knowledge statements given in Section 6.5.1.1 as mapped from Difficulty S8. This acceptable knowledge contrasts with Dhindsa's (2002) description of almost identical ideas as *misconceptions* because he limited acceptable responses to formal definitions of neutrality in terms of ionic concentrations. However, Oversby (2000a) indicates that while such formality adds to the operational model, it does not replace it. Furthermore, an operational model is still widely used in a macroscopic context by both novice and experts but Dhindsa apparently gives no credence to the more concrete model. What is more, he does not show that pre-service teachers in the study interpreted the questions as requiring a particular frame of reference (in this case theoretical). From this argument, the descriptions that Dhindsa published as 'misconceptions' can therefore be considered acceptable propositional knowledge concerning an operational model of neutrality.

The next three reported misconceptions need to be interpreted according to the Brønsted model. They are discussed in light of equations numbered shown in Figure 3.1 (see flip-out page 47)
The second instance for an anomalously reported conception comes from Hand and Treagust (1988) who reported that student understanding was unacceptable if it included definitions such as: "*A base is something that makes up an acid*". However, the Brønsted (1926) reaction scheme (Equation 3.8) clearly shows that an acid splits off a proton and becomes a base; so it would be fair to conclude that a base was making up the acid.

The next third and fourth anomalous cases both come from Linke and Venz (1979). For the third anomaly consider the reported 'misconception': "*an acid is a substance which reacts with water to form a base*". Considering Equation 3.9 representing the general Brønsted acid-base reaction and the particular example in Equation 3.11, these show that $acid_1$, HA, undoubtedly reacts with a water molecule to form $base_1$, A^-. Consequently, the conception is perfectly acceptable within the Brønsted model. The fourth anomalous 'misconception' is described by Linke & Venz as: "*a base is a substance which reacts with water to form an acid*". Similarly, applying Equation 3.12, it can be seen that $base_2$, NH_3, reacts with water and forms $acid_2$, NH_4^+ which means the fourth conception could also be acceptable according to the Brønsted model.

Furthermore, Linke and Venz (1979) reported relatively high incidences of 36% and 33%, respectively, for the two conceptions so they are unlikely to be merely idiosyncratic, but more likely the result of teaching.

As described in the Methods chapter (see Section 4.5.5.1), Johnson and Gott (1996) emphasise the importance of interpreting responses within the students' frame of reference, not the researcher's. In all three of the research publications above, neither the student interpretation nor the authors' frame of reference is clear. As a result, it is inappropriate to describe these claims as student misconceptions. This problem with alternative models being reported as difficulties reinforces the necessity for publishing the appropriate propositional knowledge against which student conceptions would be judged.

6.7 SUMMARY AND CONCLUSIONS

The analysis of the research reports with data concerning student difficulties with the species involved in acid-base chemistry has led to the following outcomes.

- Ten difficulties with acid-base species have been identified through the critical analysis in this chapter. Of these ten, three showed sub-difficulties indicating specific aspects of the main difficulty.
- There were three difficulties relating to acid-base models, three concerned general difficulties with definitions, one involved practical examples of acids and bases and three were concerned with salts and neutral solutions.
- Four instances of students' use of alternative acid-base models were shown to have been inappropriately identified as misconceptions.
- For the 17 difficulties and sub-difficulties, only five had Established descriptions (Level 4), four were Level 3, five were Level 2, and two were Level 1. It was considered inappropriate to classify one of the difficulties as it occurs much more widely than in acid-base chemistry.
- The research cohorts were mainly in senior secondary schools.
- The difficulties mapped to 53 individual propositional statements, of these 11 were implicated in more than one difficulty.
- Nearly every propositional statement was generated by the author, and verified from other sources.
- It was necessary to change some propositional statements incrementally as more difficulties became evident, particularly regards definitions and examples.

The implications of the critical analysis are discussed only briefly here as this important topic receives more extensive coverage in Chapters 9 and 10.

As Wilson (1998) found, novices and weaker students tend to organise their knowledge around categories of matter such as acid or base. These novices are not necessarily young students as the majority of research cohorts reported on in this chapter were in senior secondary classes. Consequently practitioners need to be aware of the extensive range of difficulties which students may experience with core acid-base concepts. The difficulties analysed in this chapter show three themes, namely practical links, and conceptions of ions and models. These are discussed briefly next.

According to the first theme, students apparently do not link everyday and laboratory practical experience with acid-base conceptions. This is shown by difficulties concerning everyday applications of acids and bases (S7) and the concepts of neutrality (S8) and salts (S9) which can all be addressed through empirical observations. The second theme of difficulties concerns ions present in aqueous solutions. In this regard, Sub-difficulty S1.3 and Difficulty S10 both show students’ inability to imagine ions in these solutions.

The third theme of models suggests that students deal inappropriately with acid-base models by three strategies. Firstly, they may not accommodate new models, instead limiting themselves to the one learned first (S1 and S2), as already noted by Hawkes (1992). On the other hand, they might neglect models learned earlier and question why they were not taught the ‘final’ one from the start (S3). Finally, students might create a hybrid model, appropriating aspects of each model under a single conception. This aspect of difficulties with models is not as immediately apparent, so was not discussed in the sub-category of difficulties with models (Section 6.2). However, S4 shows students mix (and muddle) acid-base definitions according to several models and S5 shows they superimpose the alkali concept from the Arrhenius model onto the Brønsted model. In essence, all three strategies imply that a single model should be applicable across all contexts. This difficulty with the nature of models, and hence the nature of science, has been shown in other contexts besides acid-base chemistry (e.g. Justi, 2000). Appropriate tuition in the different acid-base models requires that teachers and curriculum developers be aware of the differences between the models and make such propositional knowledge clear for their students. As Carr (1984) emphasises, students need clear ‘signposts’ to show where one model is more applicable than another. Furthermore, when researchers deem student conceptions to be misconceptions when these could simply represent other acceptable models of acid-base chemistry (see Section 6.6), they are themselves falling into the trap of “one model fits all’’ and so misrepresenting the nature of science. Thus, in order to specify which model authors use as a frame of reference, they should put forward propositional knowledge statements for comparison. However this was seldom the case.

Very few of the propositional statements in this chapter came directly from the research reports on student conceptions. Instead, most of them were derived by the present author from original chemistry sources in response to the mapping of conceptual difficulties. Furthermore they sometimes changed with further iterations of comparison to difficulties. Two instances of this incremental development, shown by the interim statements in Table 6.1, are evident: the definitions and the examples. Although the definitions of Brønsted acids and bases given here may still be considered ‘language-dense’ they are nevertheless more accessible than the IUPAC definition (McNaught & Wilkinson, 1997) which Bucat (2004) considers unsuitable for secondary school students.

The quality and extent of the research into different difficulties with acid-base species varies considerably. Only one difficulty (S10) had a description established through a sustained single research project. However, the critical analysis of combined outcomes from independent projects has shown that five other difficulties or sub-difficulties have also been comprehensively researched and now have accurate descriptions at Level 4 (see S1.1, S2.1, S2.4 and S7). Consequently for these difficulties, the research community needs to heed calls by Gabel (1993) and Grayson *et al.* (2001) to move beyond identifying the misconceptions; they undoubtedly exist.

Where research has not yet led to a stable description of a difficulty, or has not yet established that it occurs across multiple contexts, further investigation into its nature is needed. To be specific, three groups of difficulties need more exploration. Firstly, in the instances of students’ limited conception of bases (S1.2) and evident confusion between Arrhenius and Brønsted models for bases (S2.2 and S5) the research community needs to know whether students do not incorporate the new model for bases at all or whether they derive their own hybrid model. Secondly, the difficulty concerning muddled acid-base definitions (S4) has been found in numerous educational contexts but there is little insight into the students’ reasoning. Finally, very little has been reported on student difficulties with ions and ionic compounds such as salts (S1.3, S9 and S10) whereas Johnson (2002) argues that many unacceptable conceptions start with difficulties concerning ions. Perhaps nobody has yet designed probes to investigate the suspected and emergent difficulties. In all of these cases, researchers need to anticipate students' free responses in their interview or instrument design; probes should not be too focused.

This analysis has shown that the combined evidence from independent research projects can give considerable insight into the nature of a student difficulty. However, if researchers build upon the existing research using appropriate research strategies, many more of the student difficulties with acid-base species can be established with accurate descriptions, and so feed into appropriate teaching strategies. Ideas of what constitutes acids, bases and neutrality form the core of acid-base chemistry, on which students base their conceptions of acid-base properties. Difficulties with acid-base properties and processes are analysed in the next chapter.

CHAPTER 7

SYNTHESIS OF STUDENT DIFFICULTIES AND PROPOSITIONAL KNOWLEDGE REGARDING ACID-BASE PROPERTIES

7.1 INTRODUCTION

Following the difficulties with acid-base species presented in Chapter 6, this chapter continues the critical analysis and synthesis. Here it focuses on difficulties with reactions that occur when acids and bases display characteristic properties. This is in accordance with Wilson (1998) who found that mature chemists tend to organise their conceptions around reactions and processes rather than other more concrete classifications such as acid-base species. Accordingly, in this chapter, I address Research Question 3 which is: "*What difficulties do students experience with acid-base properties?*" As for Research Question 2, (see Chapter 6), I addressed similar sub-questions:

3a. What descriptions of difficulties with acid-base properties can be synthesised from the existing research data?

3b. How stable are these difficulty descriptions across different contexts?

3c. *What statements of propositional knowledge are needed to address the difficulties with acid-base properties?*

In the same format as used in the previous chapter, Table 7.1 gives an overall summary of the difficulties. This includes descriptions of each difficulty followed by the propositional statements to which the difficulty mapped (and their corresponding codes), together with the classification level of the difficulty. These descriptions and propositions were derived by the mapping and honing process method (see Sections 4.5 and 4.6). The difficulties in this chapter fall into four sub-categories of acid-base chemistry, namely those concerning physical properties, chemical characteristics, neutralization and finally other acid-base reactions. The discussion of these difficulty sub-categories, which follows Table 7.1, differs from that in the previous chapter because, having no control over the course content in which student difficulties were identified (see Section 3.5), a large number of individual difficulties were identified. Consequently, in the interests of brevity and to avoid monotony for the reader, some of the analyses are not shown in detail. This was instituted where a difficulty description could be synthesised from the combined data in a single step, which also led in a single step to the propositional knowledge. On the other hand, where the evidence for individual difficulties needed more than one mapping between the description and propositional knowledge, the critical analysis and reasoning are shown in greater detail.

Table 7.1 Student difficulties and propositional knowledge regarding acid-base reactions

Difficulty number	Difficulty Descriptions (In Bold) linked to Propositional Statements (coded)	Difficulty Classification
P1	**All acids, pure or in solution, are corrosive or can “burn”.**	4
	Properties in concentrated solutions may differ from those in dilute solutions. (1.2.0.1)	
	Some acids can be corrosive and appear to ‘burn’ skin and eyes. (2.1.1.4)	
	Citric acid is irritating to eyes and skin. (2.1.1.4.3.1)	
P2	**Acids are poisonous or toxic.**	4
	Foods often contain acidic substances. (2.1.2.1)	
P3	**Bases are dangerous**	3+
	Basic substances are found in cleaning materials such as oven cleaner, household ammonia, household bleach; washing soda, Na_2CO_3 and soap (3.1.2.1)	
	Alkali is an alternative term for Arrhenius bases (3.2.1.1)	
P4	**Acids and bases have dichotomous properties**	3
	Acids and bases have complementary properties. (1.2.0.2)	
	As solutions become more acidic the pH decreases (9.3.1)	
	As solutions become more basic the pH increases (9.3.2)	
P4.1	**All substances are either acid or base.**	1
	Neutral substances are neither acid nor base (5.1)	
P4.2	**Bases are not dangerous.**	4
	Bases such as NaOH, KOH and ammonia (3.1.1.4.1) can be corrosive (or caustic) and appear to ‘burn’ skin or eyes. (3.1.1.4)	
	Sodium and potassium hydroxides have common names caustic soda and caustic potash (3.1.1.4.1.1)	
	Oven cleaner and drain cleaner contain basic substances such as NaOH. (3.1.2.1.1)	
P5.1	**Only acidic substances have taste.**	1
P5.2	**Acidic taste is called bitter.**	2
P5.3	**Acid solutions taste sweet.**	1
	Weakly acidic solutions taste sour. (2.1.1.3), as do lemons. (2.1.1.3.1)	
	Weakly basic substances taste bitter (3.1.1.3), as does soap (3.1.1.3.1)	
P6	**Acids are recognized by strong smells**	3
	Acidic substances may smell ‘sharp’ (2.1.1.5.1) and may make you feel like choking (2.1.1.5.1.1)	
	Ammonia has a strong pungent smell (3.1.1.5.1), as does urine. (3.1.1.5.1.1)	
P7	**Bases do not have a characteristic feel.**	1
	Weakly basic solutions feel soapy (3.1.1.4.2)	
P8	**Acidic or basic solutions do not have characteristic properties**	3+++
	Indicators have characteristic colours in acidic (2.1.1.2) or basic solutions. (3.1.1.2)	
	Acidic solutions have a pH less than 7. (2.1.1.1)	
	Basic solutions have a pH greater than 7. (3.1.1.1)	
P9	**Acids and bases have their own characteristic colours**	3+
	Indicators are substances that change colour at certain pH values (6.1.2) and can be added to solutions of acids and bases (6.1.1)	
	Indicators have characteristic colours in acidic (2.1.1.2) and basic solutions. (3.1.1.2)	
P10	**pH applies only to acidity.**	4
	pH is an indirect practical scale (9.2.1) of acidity and alkalinity. (9.2.2)	
	pH is an alternative method of representing hydrogen ion concentration, $[H^+]$. (9.4.1.1)	
P10.1	**Salt solutions do not have a pH.**	2
	pH can be found for any aqueous solution, including salts. (9.1)	
	NaCl forms a neutral aqueous solution (5.1.2)	

Difficulty number	Difficulty Descriptions (In Bold) linked to Propositional Statements (coded)	Difficulty Classification
P11	**Acids contain bubbles**	3+
P11.1	**All acid-base reactions produce gases**	1
	When acids react with some metals, hydrogen is produced (2.1.1.7) Interim see P19	
	When acids react with carbonates, carbon dioxide is produced. (2.1.1.6.2) Interim see P19	
	When acids react with basic oxides or hydroxides, no gases are produced except water vapour. (2.1.1.6.1) Interim see P19	
P12.1	**Higher pH shows greater acidity.**	4
P12.2	**Lower pH's shows greater alkalinity or basic nature.**	2
P12.3	**Acidic pH is less than 7, but higher pH shows greater acidity.**	3
	pH is an indirect practical scale (9.2.1) of acidity and alkalinity. (9.2.2)	
	Acidic solutions have a pH less than 7 (2.1.1.1)	
	As solutions become more acidic, the pH decreases. (9.3.1)	
	Neutral solutions have a pH of 7. (5.1.1)	
	Basic solutions have a pH greater than 7 (3.1.1.1)	
	As solutions become more basic the pH increases (9.3.2)	
	pH is an alternative method of representing hydrogen ion concentration, $[H^+]$. (9.4.1.1)	
	As [H+] increases, the pH decreases. (9.4.2.1)	
	As $[OH^-]$ increases the pH will increase. (9.4.2.2)	
	A neutral solution is one where $[H^+] = [OH^-]$.(5.2)	
	Hydrogen ion concentration and hydroxide ion concentration are related by K_w. (9.6.2.1)	
	K_w is an equilibrium constant (9.6.2.1.2), given by: $K_w = [H^+].[OH^-]$. (9.6.2.1.1) at 25^oC	
	$K_w = 1.0 \times 10^{-14}$ (9.6.3.1)	
P13	**An indicator can test whether an acid is strong or weak.**	1
	Arrhenius acid-base strength is measured by the conductivity of their solutions (8.2.3)	
	Indicators are substances that change colour at certain pH values. (6.1.2)	
P14	**All indicators change colour at the same pH value**.	1
	The pH range over which indicators change colour is characteristic for each indicator. (6.1.2.1)	
P15	**Neutralization reactions between alkalis and acids produce insoluble salts**	2
	During neutralization reactions, cations from the base and anions from the acid form a salt. (7.2.2)	
	The solubility of salts depends on the particular ions involved. (7.2.2.1)	
P16	**Every neutralization reaction produces a neutral solution**	4
	Titrations use neutralization reactions between equivalent amounts of acids and bases (7.1.3), which in principle, react completely. (7.1.3.1)	
	Neutralization reactions result in a solution that may be acidic, basic or neutral. (7.2.3)	
	When equivalent amounts of a strong acid and an equally strong base react, the resulting solution will be neutral. (7.2.3.1)	
	When equivalent amounts of acid and base of unequal strength react, the resulting solution will not be neutral. (7.2.3.2)	
	Neutralization reactions between equivalent amounts of weak acids and strong bases result in basic solutions. (7.2.3.2.2)	
	Brønsted neutralization in water is the reaction between H_3O^+ and OH^- ions (7.3.3.1.1) which may be represented as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$ (10.3.2.1)	
	If neutralization reactions involves weak acid or base molecules there will be at least two competing equilibria (7.3.3.1.3)	
	As a base, acetate ion, Ac^-, is stronger than its conjugate HAc is an acid. (8.3.3.1)	
	A stronger conjugate base in water will compete for H_3O^+ ions (7.3.3.1.3.1)	
	as shown by: $H_3O^+(aq) + Ac^-(aq) \rightleftharpoons H_2O(l) + HAc(aq)$ (10.3.4.2)	
P17	**No heat is evolved during neutralization reactions; OR, Heat is absorbed during neutralization reactions**	2
	The acid-base neutralization reaction will cause a temperature rise (7.1.4)	

Difficulty number	Difficulty Descriptions (In Bold) linked to Propositional Statements (coded)	Difficulty Classification
P18	**Strong acids perform better than weak acids.** Acid or base strength depends on the chemical nature of the acid or base. (8.1) All neutralization reactions produce the same heat of reaction. (7.2.4.1) The different heat of reaction measured for weak acids is due to the extent of dissociation of molecules (7.2.4.2) For acid-base titrations indicators are chosen so that the end-point of a titration is also the equivalence point. (7.1.3.2) In principle, equivalent amounts react completely (7.1.3.1) For monoprotic acids, the rate of reaction for a weak acid (or base) will be less than from an equally concentrated strong acid (or base) (7.1.5), although the amount of product produced will be the same (7.1.6)	2
P19	**Neutralization is mixing, not a chemical reaction.** Neutralization is a process whereby acidic and basic substances react chemically to produce new substances (7.1), which include a salt (7.1.2.1); and in aqueous solutions, water is formed. (7.1.2.2) Acids and basic oxides or hydroxides react chemically but produce no gases except water vapour (2.1.1.6.1) Acids and carbonates react chemically to also produce carbon dioxide (2.1.1.6.2) Acids and some metals react chemically to produce a salt and hydrogen (2.1.1.7)	n/a
P20	**Acid - base reactions are additive** Neutralization is a double decomposition (or metathesis) reaction. (7.1.1)	n/a
P20.1	**Indicators are necessary for or assist with neutralization.** Indicators are used in very small amounts, about 8 drops per 100 ml. (6.1.1.2) Indicators are substances that change colour at certain pH values (6.1.2)	4
20.2	**Acid-base neutralization is neutralization of oppositely charged ions.** Electric charge is irrelevant to the acid-base function. (10.2.0.1) Arrhenius neutralization is the reaction between hydrogen ions and hydroxide ions (7.2) to produce water (7.2.1) During neutralization, cations from the base and anions from the acid form a salt. (7.2.2) Brønsted neutralization in water is a reaction between H_3O^+ and OH^- ions (7.3.3.1.1) which may be represented as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$ (10.3.2.1)	4
P21	**Acids are stronger than bases.** Acid or base strength depends on the chemical nature of the acid or base (8.1) Strong Arrhenius acids and bases are fully dissociated in solution. (8.2.2.1) Strong Brønsted acids are good proton donors. (8.3.1) Interim, see P24 Strong Brønsted bases are good proton acceptors. (8.3.2)	3++
P21.1	**The product of neutralization is acidic** Neutralization reactions result in solutions that may be acidic, basic or neutral. (7.2.3) When equivalent amounts of a strong acid and an equally strong base react, the resulting solution will be neutral. (7.2.3.1)	3
P22	**Acids and bases consume each other** For acid-base titrations, in principle equivalent amounts react completely (7.1.3.1) Brønsted reactions are, in principle, reversible. (7.3.2) Brønsted neutralization in water is a reaction between H_3O^+ and OH^- ions (7.3.3.1.1) which occurs to a large extent, but not completely (7.3.3.1.2) Brønsted acid and base react to form Brønsted base and acid (7.3)	1
P23	**Conjugate acid-base pairs are both strong or both weak.** Strength of acid-base conjugates is complementary. Stronger acids give rise to weaker conjugate bases and vice versa. (8.3.3)	2

Difficulty number	Difficulty Descriptions (In Bold) linked to Propositional Statements (coded)	Difficulty Classification
P24	**The Arrhenius model is for strong acids and the Brønsted model is for weak acids.** Strong Arrhenius acids or bases are fully dissociated in solution (8.2.2.1) Weak Arrhenius acids are partially dissociated in solution (8.2.2.2) Stronger Brønsted acids are better proton donors than weaker Brønsted acids. (8.3.1)	2
P25.1	**All salts have neutral aqueous solutions.**	2
P25.2	**Sodium chloride does not have a neutral aqueous solution.** Salts may have neutral or non-neutral solutions (7.1.3) Salts where ions are weaker Brønsted acids or bases than water will have neutral solutions. (7.3.3.3.2.1) such as NaCl (5.1.2) Salts where ions are stronger Brønsted acids than water will have acidic solutions. (7.3.3.3.2.2) Salts where ions are stronger Brønsted bases than water will have basic solutions (7.3.3.3.2.3) such as sodium ethanoate (5.1.3.1)	2
P26	**There is no acid-base reaction between water and the ions from a salt.** Ionic compounds dissociate into cations and anions when they dissolve in water (8.2.5.1) If ions are stronger Brønsted acids or bases than water, they will react with water molecules. (8.3.5) Hydrolysis of anions or cations changes the [H_3O^+] and [OH^-] (8.3.5.2) Brønsted acid-base reactions include hydrolysis. (7.3.3.3) Hydrolysis is a chemical reaction between an ion or molecule and water (7.3.3.3.1)	3+

7.2 DIFFICULTIES WITH PHYSICAL PROPERTIES OF ACIDS AND BASES

This section considers student conceptual difficulties that have been identified concerning the macroscopic, physical characteristics of acidic and basic substances. The difficulties can be categorised according to alleged dangers of acids and bases, a dichotomous conception of their properties and their individual sensory properties.

7.2.1 Conceptions of the danger of acids and bases

Numerous authors highlight a widespread conception that acids are dangerous, sometimes in contrast to the conception of bases. For instance Chiu (2007) reports that about a quarter of elementary school students in Taiwan thought a solution was harmful if it was an acid. Additionally, Ogunniyi and Mikalsen (2004) found "the notion that acids are dangerous while bases and neutral substances are not" among South African and Norwegian students. On examination, these generalizations could be separated into distinct conceptions, which are outlined below.

7.2.1.1 Difficulty P1: All acids, pure or in solution, are corrosive or can "burn".

Several independent studies, among secondary students up to Grade 10, report conceptions which all suggest the corrosive ability of acidic solutions (Hand & Treagust, 1988; Nakhleh, 1994; Ross & Munby, 1991; Toplis, 1998; Ogunniyi & Mikalsen, 2004; Lin & Chiu, 2007). The data support the difficulty description: *All acids, pure or in solution, are corrosive or can* *"burn"*. With a stable description across multiple research studies in different contexts, the difficulty can be classified at Level 4. From the research in the reports given above, students seem to over generalise, as not all acids are corrosive. Moreover, students appear to make no distinction between pure acids and solutions of these. Neither do they distinguish between concentrated and dilute solutions. Consequently the difficulty maps to the following propositional knowledge:

- Some acids can be corrosive and appear to burn the skin and eyes. (2.1.1.4) (Young, 2003b),
- Citric acid is irritating to eyes and skin. (2.1.1.4.3.1) (Young, 2003b).
- Properties in concentrated solutions may differ from those in dilute solutions. (1.2.0.1)

This difficulty may be related to Difficulty S1 concerning the lack of distinction which students make between acids and their solutions (see Section 6.2.1.1).

7.2.1.2 Difficulty P2: Acids are poisonous or toxic

Coupled with the previous difficulty, students at all levels, from junior secondary to tertiary and even teachers, are fearful about ingesting acidic substances (Cros *et al.*, 1986; Ross & Munby, 1991; Toplis, 1998; Demircioğlu *et al.*, 2004; Ogunniyi & Mikalsen, 2004; Drechsler & Schmidt, 2005b; Chiu, 2007). The common essence of their descriptions is: *All acids are poisonous or toxic*. Being found in multiple contexts through independent triangulated studies, I classified this difficulty at Level 4. It appears that students are unaware that many foodstuffs are acidic, which relates to Difficulty S7 concerning everyday examples of acidic and basic substances (see Section 6.4.1). In particular, students may be interested to find phosphoric acid in the list of ingredients in Coca Cola or that they would need to ingest half a kilogram of citric acid (used in sour sweets) for it to be fatal (Young, 2003b). Moreover, if students believe acids are corrosive (Difficulty P1 in the previous section) it is not surprising that they will not ingest them. The corresponding propositional knowledge which has already been given in the previous chapter is:

- Foods often contain acidic substances. (2.1.2.1)

7.2.1.3 Are difficulties P1 and P2 distinct difficulties?

Is it worth separating the difficulties P1 and P2 – could they be one difficulty: 'acids are dangerous'? If the implications of the student reasoning are different then according to the method outlined in Section 4.5 they should be treated separately. I first consider the implication of acids being 'poisonous'. The word 'acid', coined in the 17th century, came from the Latin word *acidus* meaning sour or tart. Consequently, the characteristic acidic taste is inherent in the operational model. Furthermore, an important application of acid chemistry is in food science. What is more, this conception misleads students into thinking that only acids are poisonous. Moreover, while many acidic substances are poisonous, this is not necessarily due to their acidic nature. Secondly, what are the implications of a student belief that acids are corrosive? Perhaps students might think that only acids are corrosive, hence they might misclassify some caustic bases as acids. In summary, acids are indeed dangerous, but student difficulties with their corrosive and poisonous properties each have different educational consequences, and so they should be treated as separate difficulties.

7.2.1.4 Difficulty P3: Bases are dangerous

Some junior secondary and elementary students see bases as dangerous, along with acids. From the limited data (Toplis, 1998; Chiu, 2007), the description is not yet entirely clear. Further research is needed to verify whether students distinguish the two aspects as they did with acids. Consequently, the classification of the difficulty is only Level 3+.This difficulty maps to the following two propositional knowledge statements – both already appeared in the previous Chapter (see Difficulties S5 and S7):

- Alkali is an alternative term for Arrhenius bases. (3.2.1.1)
- Basic substances are found in cleaning materials such as oven cleaner, household ammonia, household bleach; washing soda Na_2CO_3, and soap. (3.1.2.1)

7.2.2 The acid-base dichotomy

7.2.2.1 Difficulty P4: Acids and bases have dichotomous properties

In addition to a conception that bases are harmless, Nakhleh and Krajcik (1994) identified acid-base dichotomy as a major theme of student conceptions which they substantiate with student quotations such as: “if acids are coloured, bases are clear” and: “if acids taste bitter, bases taste sweet”. Without further analysis I can describe the difficulty as: *Acids and bases have dichotomous properties*. From one comprehensive study the difficulty is classified at Level 3. The difficulty description is based at present on macroscopic observations; it may also pertain to student sub-microscopic understanding of acid-base systems, however no research in this regard arose in the search of publications (see results in 5.2). In the interim, the difficulty maps to a complementary, as opposed to inverse, relationship between acidic and basic properties as shown by the following propositional knowledge:

- Acids and bases have complementary properties. (1.2.0.2)
- As solutions become more acidic the pH decreases. (9.3.1)
- As solutions become more basic the pH increases. (9.3.2)

Difficulty P4 is not trivial, as it could inhibit further conceptual development. In this regard, in Section 6.5.1.2 it was argued that students resisted the idea of a substance or species being able to act as both acid and base; that is, being amphoteric (Difficulty S9). The conception may be explained by a dichotomous view of acid-base substances, which would preclude a substance falling into both classifications. Further open-ended research on Difficulty S9 may show that it is a sub-difficulty of P4. Other implications of the Difficulty P4 are given as sub-difficulties below.

7.2.2.2 Sub-difficulty P4.1: All substances are either acid or base.

Arising from the dichotomous view above, students classify every substance as acid or base. The description of the difficulty, given above, is based on my own interpretation of the data from Nakhleh and Krajcik (1994) and consequently it cannot be classified as more than Level 1, or Suspected.

- Neutral substances and solutions are neither acidic nor basic. (5.1)

7.2.2.3 Sub-difficulty P4.2: Bases are not dangerous.

Published research shows students believe bases to be harmless (Ross & Munby, 1991; Nakhleh & Krajcik, 1994; Toplis, 1998; Ogunniyi & Mikalsen, 2004). This contrasts so clearly with the common perception of acids as corrosive or poisonous that I believe it arises from the dichotomous conception. The descriptions in the published research map to the following scientific knowledge related to everyday examples and safety aspects.

- Oven cleaner and drain cleaner contain basic substances such as NaOH. (3.1.2.1.1)
- Bases, such as NaOH and KOH and ammonia (Young, 2003a) (3.1.1.4.1), can be corrosive (or caustic) and appear to ‘burn’ skin and eyes. (3.1.1.4)
- Sodium and potassium have common names caustic soda and caustic potash. (3.1.1.4.1.1)

The propositional statements given above, in turn suggests the sub-difficulty description: *Bases are not dangerous.* This conception has been found in triangulated studies covering four different cohorts around the world, so I can classify it at Level 4, or Established.

7.2.3 Difficulties concerning sensory properties of acidic or basic solutions

Three student difficulties (one with sub-difficulties) concerning physical properties of acids and bases can be described directly from the original research. The research, from which the descriptions were derived, concerning taste (P5) and smell (P6) of acids and feel (P7) of bases, is summarised below (Table 7.2). For each difficulty, the propositional knowledge statements to which it could be mapped are given below the evidence.

Table 7.2 Summary of research on acid-base sensory properties

Difficulty number	**Difficulty description**	**Classification level**	**Reason for classification**	**Educational level of students**	**Author(s)**
P5.1	Only acidic substances have taste.	1	Unanticipated data	Senior secondary Pre-service teachers	Nakhleh & Krajcik (1994) Dhindsa (2002)
P5.2	Acidic taste is called bitter.	2	Little research reported, could be a language difficulty (Clerk & Rutherford, 2000)	Senior secondary Senior secondary Pre-service teachers	Ross & Munby (1991) Nakhleh & Krajcik (1994) Bradley & Mosimege (1998)
P5.3	Acid solutions taste sweet.	1	Unvalidated MCQ distractor	Pre-service teachers	Bradley & Mosimege (1998)
	• Weakly acidic solutions taste sour. (2.1.1.3), as do lemons. (2.1.1.3.1) • Weakly basic substances taste bitter (3.1.1.3), as does soap (3.1.1.3.1)				
P6	Acids are recognized by strong smells	3	Two studies combined to give the same picture	Senior secondary Senior secondary	Ross & Munby (1991) Nakhleh & Krajcik (1994)
	• Acidic substances may smell 'sharp' (2.1.1.5.1) and may make you feel like choking (2.1.1.5.1.1) • Ammonia has a strong pungent smell (3.1.1.5.1), as does urine. (3.1.1.5.1.1)				
P7	Bases do not have a characteristic feel.	1	Unvalidated MCQ distractor	Pre-service teachers	Bradley & Mosimege (1998)
	• Weakly basic solutions feel soapy (3.1.1.4.2)				

- Corresponding propositional statements shown bulletted

Difficulty P6 has the highest classification because data from two reports gave a coherent 'picture', while the other difficulties all have low classifications due to the lack of reported research data to substantiate coherent difficulty descriptions. In particular, Bradley and Mosimege (1998) gave no indication of any research on which they based distractors used in two multiple-choice items, resulting in little insight being gained into the nature of the relevant difficulties (P5.3 and P7).

7.3 DIFFICULTIES WITH ACID-BASE CHEMICAL CHARACTERISTICS

In the previous chapter, Difficulty S1 described students' use of an operational model of properties to define acids and bases (see Section 6.2.1.1). Even more fundamentally, research shows that either students have trouble even recognising or applying characteristic chemical properties to classify substances as acid or base, or they do not interpret the observations appropriately. These two aspects are discussed in the following subsections.

7.3.1 Difficulties with characterising properties of acid-base substances

The idea of chemical properties characterising acids and bases as classes of substances is the core of an operational model (see Section 3.3.1). This section shows that some students do not understand fundamental ideas inherent in chemical classification, or they might give an inappropriate meaning to observations of the properties.

7.3.1.1 Difficulty P8: Acidic or basic solutions do not have characteristic properties.

Research has shown that elementary and junior secondary students, and some elementary teachers, do not know how to differentiate the acidic or basic solutions (Ogunniyi & Mikalsen, 2004; Chiu, 2005). Furthermore, students, even in 10th Grade, do not use characteristic chemical properties such as indicators (Furió-Más *et al.*, 2007) or they suggest inappropriate characteristics (such as toxicity, corrosive ability or strong flavours) to determine a solution's acidity or basicity (Hand & Treagust, 1988; Lin & Chiu, 2007). The difficulty maps to the following propositional knowledge concerning essential chemical properties of such solutions (Hand, 1989):

- Acidic solutions have a pH less than 7. (2.1.1.1)
- Basic solutions have a pH greater than 7. (3.1.1.1)
- Indicators have characteristic colours in acidic solutions (2.1.1.2) and basic solutions (3.1.1.2)

The research described above was reported as carefully triangulated, and all give a coherent picture of the conception as described above. However, the description still remains vague and needs sharpening. Consequently, the difficulty classification can only remain at Level 3+++. Further research should probe two aspects: whether students are unaware of the characteristic acidic or basic properties or more fundamentally, whether they do not realise these properties can be used for classification purposes. The next three difficulties add to the latter contention.

7.3.1.2 Difficulty P9: Acids and bases have their own characteristic colours

The notion of colour as a property of the acid or base itself, rather than due to an indicator dye has been reported from two studies, concerning junior secondary students (Botton, 1995) and senior secondary students (Nakhleh & Krajcik, 1994). The difficulty maps directly to the following propositional knowledge:

- Indicators are substances that change colour at certain pH values (6.1.2) and can be added to solutions of acids and bases. (6.1.1)
- Indicators have characteristic colours in acidic solutions (2.1.1.2) and basic solutions. (3.1.1.2)

Reversing the statements leads to the difficulty description given above. The classification of the difficulty description as Level 3+ follows from this research in two contexts. A practically based teaching program has been reported as completely correcting this misconception (Demircioğlu *et al*., 2005).

7.3.1.3 Difficulty P10: pH applies only to acidity

Student belief that pH only applies to acidity, instead of both acidity and basicity has been reported by five research groups involving work with senior students (see Table 7.3 below). The levels of prevalence are often over 10%, indicating a problem that needs addressing as it will inhibit student understanding of pH as a characteristic of acidic, basic and neutral solutions.

Table 7.3 Research into student conception of pH limitation to acids

Incidence	Educational level	Author(s)
Not applicable	Senior secondary	Ross & Munby (1991)
19%	Senior secondary	Sheppard (2006)
17% to 13%	Tertiary	Cros *et al.* (1986; 1988)
Not applicable	Tertiary	Zoller (1996)
6%	Pre-service teachers	Dhindsa (2002)

The consistency of these research reports leads to the honed description: *pH applies only to acidity,* and allows the difficulty to be classified at Level 4. However, a number of chemistry education experts have at times also described pH simply as a measure of acidity (e.g. Hawkes, 1994; Oversby, 2000a). While undoubtedly these experts know that pH also applies to basic or alkaline solutions nevertheless students appear to need this tacit knowledge to be made explicit, as in the following propositional knowledge concerning a qualitative meaning for pH:

- pH is an indirect practical scale (9.2.1) of acidity and alkalinity. (9.2.2) (Sörenson, 1909; Hawkes, 1994)

For more advanced students, the following propositional statements will contribute a richer understanding of pH.

- pH is an alternative method of representing hydrogen ion concentration, $[H^+]$ (9.4.1.1) (Dhindsa, 2002).

The difficulty has also a corollary given as the following sub-difficulty.

7.3.1.4 Difficulty P10.1: Salt solutions do not have a pH

The conception P10.1 has been thinly reported, with little substantiating qualitative evidence (Bradley & Mosimege, 1998; Demircioğlu *et al*., 2005). Consequently, the provisional difficulty description given above is classified as Level 2, or Emergent. It maps to the propositional knowledge below:

- pH can be found for any aqueous solution, including salts (9.1) (Hawkes, 1994).
- NaCl forms a neutral aqueous solution (5.1.2)

The difficulty is likely to follow from the reasoning in Difficulty P10, accordingly it is considered as a sub-difficulty. Further exploratory research should seek to answer questions such as: Is this conception something to do with ‘neutral’ not registering as pH and does it pertain to all salt solutions? Or is the difficulty perhaps a result of students reasoning that only acids having pH, in which case do students think bases also have no pH?

7.3.1.5 Difficulty P11: Acids contain bubbles

Two research projects have identified a student conception that acids themselves contain bubbles (Nakhleh & Krajcik, 1994; Erduran, 2003) and from these, without further analysis the difficulty can be described as shown above. Erduran’s results complement the triangulated study by Nakhleh and Krajcik (1994) and so the conception has been found in two contexts, which means the difficulty description can now be classified as Level 3+, or Partially Established. Talanquer (2006, p 813) offers an explanation for the difficulty. In his analysis, students sometimes think “some qualities seem ... to exist independently of the entities that possess them”. Within this framework, the bubbles were there all along; they were just hidden. Accordingly, students do not understand the bubbles as being a result of an acid reaction. This framework of reasoning will also explain the following sub-difficulty. Both P11 and P11.1 map to the same propositional knowledge statements, which are given in the next section below.

7.3.1.6 Difficulty P11.1: All acid reactions produce gases.

Perhaps having seen bubbles produced in the reaction between a carbonate or some metals and an acid, students may believe that all acid reactions produce bubbles. To be specific, research evidence shows the erroneous belief that a gas was produced in the reaction between acid and metal hydroxide (Ross & Munby, 1991) or acid and metal oxide (Tan *et al.*, 2002). I can only describe Difficulty P11.1 at Level 1, as there had been little controlled research on this aspect. The following propositional knowledge applies to both P11 and P11.1.

- When acids react with some metals hydrogen is produced. (2.1.1.7)
- When acids react with carbonates, carbon dioxide is produced. (2.1.1.6.2)
- When acids react with basic oxides or hydroxides, no gases are produced except water vapour. (2.1.1.6.1)

7.3.2 Difficulties interpreting empirical observations to identify acids and bases

Even if students already understand the notion of characteristic acid-base properties, the following three difficulties show that they do not interpret evidence of pH or indicator colour change appropriately.

7.3.2.1 Difficulty P12: Higher pH shows greater acidity – Lower pH shows greater alkalinity

Three closely aligned sub-difficulties with pH are presented under this difficulty; there is not yet enough evidence to say how or even if, they are linked in students' minds. In the first case, there is the notion that higher pH is related to greater acidity as shown in the Grade 12 student quotation: "Oh, a strong acid would be more acidic meaning probably it has a higher pH" (Ross & Munby, 1991). Similar ideas were reported among junior secondary students (Toplis, 1996), senior secondary (Linke & Venz, 1979; Lambert, 2005; Ouertatani *et al*., 2007) and pre-service teachers (Bradley & Mosimege, 1998; Dhindsa (2002). From the results of all these research projects, the conceptions as described below are evident. However, the notion for basic solutions has been less extensively reported (only Linke & Venz, 1979; Toplis, 1996) than that for acidic solutions. Consequently there still remains a question of whether students in fact reverse the whole pH scale. Accordingly, I have separated the conception into the two descriptions given below, to reflect the disparity in the depth of research:

Difficulty P12.1: Higher pH shows greater acidity: Level 4, and

Difficulty P12.2: Lower pH's shows greater alkalinity or basic nature; Level 3

I suggest that novice students need to integrate the explicit propositional knowledge that follows:

- pH is an indirect practical scale (9.2.1) of acidity and alkalinity. (9.2.2)
- Acidic solutions have a pH of less than 7. (2.1.1.1)
- As solutions become more basic, the pH increases (Hawkes, 1994). (9.3.2)
- Basic solutions have a pH of greater than 7. (3.1.1.1)
- As solutions become more acidic, the pH decreases (Hawkes, 1994). (9.3.1)
- Neutral solutions have a pH of 7 (Dhindsa, 2002) (5.1.1)

Both these sub-difficulties could simply be mistakes (that is simply ‘forgetting’) which are easily corrected (Abimbola, 1988). However, the first difficulty was identified among senior students so it is likely to be deep-seated, perhaps following from the belief that pH only applies to acids (see Section 7.3.1.3) along with the heuristic ‘more A, therefore more B’ reported by Stavy and Tirosh (2000). This reasoning might be so deeply ingrained that when students learn that pH also applies to bases, they simply reverse the reasoning for bases. The next sub-difficulty indicates a transition stage before a scientific conception is achieved.

7.3.2.2 Difficulty P12.3: Acidic pH is less than 7, but higher pH shows greater acidity

Bradley and Mosimege (1998) reported responses to multiple-choice item from pre-service teachers. These authors asked students to choose the most acidic solution from those with a pH of 3, 4, 6, 7 or 9. Instead of the correct option of 3, or perhaps the highest option, 9, indicating Difficulty P12.1, about 10% of the students chose the options of 6 or 7. The students appear to still believe that a higher pH shows greater acidity while also knowing the scientific principle that (at 25°C) acidic solutions have pH less than 7. Accordingly, this difficulty can map to the same propositional knowledge already used for Difficulty P12. Similar conceptions are reported by Dhindsa (2002), also from pre-service teachers, that is older students, lending weight to my conjecture that this is a transition or liminal (Perkins, 1999) stage for students. Both Grayson (1996) and Hammer (2000) view such as situation as a resource for learning, rather than a concept to be substituted. Therefore, it is frustrating that neither Bradley and Mosimege (1998) nor Dhindsa (2002) explores this Difficulty P12.3 any further, leaving it with a low classification of Level 2, or Emergent. In this regard, some questions remain unanswered, for example, do these students conceive the pH of basic solutions scientifically or as for Difficulty P12.2? Further research should continue to use open-ended techniques to probe the nature of the sub-difficulty.

7.3.2.3 Difficulty P13: An indicator can test whether an acid is strong or weak.

Bradley and Mosimege (1998) report a student difficulty described as above, concerning the role of indicators. Being unanticipated data (a single quotation) in response to an open-ended question I class the description as Suspected or Level 1. While historically indicators were used to rank the strength of acids and bases because of their different colour transition points (Szabadváry, 1964), this role has become obsolete with electrolytic measurements. Accordingly, the difficulty maps to the following propositional knowledge.

- Indicators are substances that change colour at certain pH values. (6.1.2)
- Arrhenius acid or base strength is measured by the conductivity of their solutions (8.2.3)

7.3.2.4 Difficulty P14: All indicators change colour at the same pH value

Some students thought that any indicator was expected to change colour when the pH was 7, while others insisted this colour change would not happen until the solution became acidic, although no further details are given (Sheppard, 2006). This difficulty description could explain why 70% of the students in Bradley and Mosimege's (1998) study (see Difficulty P13 above) were unable to predict which indicator to use for titrations with different combinations of acid-base strength. Being based on my own interpretation of the data, I only classify the difficulty as Level 1, or Suspected. It maps to the propositional knowledge below:

- The pH range over which indicators change colour is characteristic for each indicator. (Szabadváry, 1964). (6.1.2.1)

7.4 DIFFICULTIES WITH ASPECTS OF NEUTRALIZATION REACTIONS

In the matter of neutralization reactions between acids and bases, as in the previous section, students do not make appropriate links between empirical observations and theoretical concepts. The difficulties in this section concern macroscopic observations as well as interpretations of these observations.

7.4.1 Difficulties with macroscopic aspects of neutralization reactions

The difficulties described in this sub-section reflect inappropriate empirical observations of a product of neutralization reactions, the neutrality (or otherwise) of the end-point and heat of reaction

7.4.1.1 Difficulty P15 Neutralization reactions between alkalis and acids produce insoluble salts

The conception above has been reported by Tan *et al.* (2002) but not pursued further. As a result, the difficulty is classified as Level 2, or Emergent. At this stage, not knowing the cause of the conception, the difficulty maps to very general propositional knowledge, given as:

- During neutralization reactions, cations from the base and anions from the acid form a salt. (7.2.2)
- The solubility of salts depends on the particular ions involved. (7.2.2.1)

7.4.1.2 Difficulty P16: Every neutralization reaction produces a neutral solution

The description of the misconception published as: "Every neutralization reaction yields a neutral solution" comes from comprehensive research described is sufficient detail to show that the misconception exists in different chemical contexts, and among several different student cohorts (Schmidt, 1991; 1995). Consequently it is possible for a single comprehensive research study to 'move' a description of a student conception right through the classification framework up to Level 4. This research was evaluated as being of high quality (see Section 5.4.1) as it started appropriately with free-response interviews, only later becoming more focused, and furthermore it involved large numbers of students from different educational cohorts. Schmidt (1991) attributes the conception to the word 'neutralization' becoming firmly entrenched before students are introduced to weak acids and bases, and so it was termed a "hidden persuader". In this regard, the propositional knowledge given by Nakhleh and Krajcik (1994) is of concern. They state that: "Acids react with bases to form a salt; this is called a neutralization reaction. In aqueous solutions, water is often formed". There is no problem with these statements but then they continue: "this occurs at pH 7". Their research context included both weak and strong acids, so the pH of the end point would not always have been 7. Such propositional knowledge is misleading. I sought appropriate propositional statements in the macroscopic domain (as given below) because students are likely to encounter neutralization reactions before they are familiar with ions.

- Titrations use neutralization reactions between equivalent amounts of acids and bases (7.1.3), which in principle, react completely. (7.1.3.1)
- Neutralization reaction results in a solution that may be acidic, basic or neutral. (Schmidt, 1991) (7.2.3)
- When equivalent amounts of a strong acid and an equally strong base react, the resulting solution will be neutral (Schmidt, 1995). (7.2.3.1)

- When equivalent amounts of an acid and base of unequal strength react, the resulting solution will not be neutral (Schmidt, 1995). (7.2.3.2)
- Neutralization reactions between equivalent amounts of weak acids and strong bases result in basic solutions. (Drechsler & Schmidt, 2005b). (7.2.3.2.2)

In describing his work, Schmidt gives propositional knowledge in more abstract terms of hydrogen and hydroxide ions suitable for more advanced students. Accordingly, the statements given below, which are based on Nakhleh and Krajcik (1994) and Schmidt (1997) reflect these more sophisticated ideas.

- Brønsted neutralization in water is the reaction between H_3O^+ and OH^- ions (7.3.3.1) represented by $H_3O^+(aq) + OH^-(aq) \rightleftharpoons 2\ H_2O(l)$ (10.3.2.1)
- If neutralization reactions involves weak acid or base molecules, there will be at least two competing equilibria (7.3.3.3.1)
- As a base, acetate ion, Ac^-, is stronger than its conjugate HAc is an acid. (8.3.3.1)
- A strong conjugate base will compete for H_3O^+ ions (7.3.3.3.1.1) as given by: $H_3O^+(aq) + Ac^-(aq) \rightleftharpoons H_2O(l) + HAc(aq)$ (10.3.4.2)

7.4.1.3 Difficulty P17 No heat is evolved (OR Heat is absorbed) during neutralization reactions

Results from two research groups indicate difficulty among senior secondary and tertiary students with the observation that heat is released during an acid-base reaction (see Table 7.4).

Table 7.4 Research concerning heat of reaction for acid-base reaction

Assertion	Percentage of students in agreement with assertion	Educational level of students	Authors
There is a temperature change when a solution of a base is added to an acid	41	1st year university	Cros *et al.* (1986)
There is a temperature change when a solution of a base is added to an acid	47	After 1 year at university	Cros *et al.* (1988)
In the acid-base reaction there is evolution of heat	29	Senior secondary	Vidyapati & Seetharamappa (1995)
In the acid-base reaction there is absorption of heat	15	Senior secondary	Vidyapati & Seetharamappa (1995)

All three publications mentioned above report on highly focused research probes in a true/false format. Furthermore, not one report gives qualitative evidence to substantiate the authors' descriptions. In particular, Cros *et al.* (1986) do not show how the student response of 'false' to the statement about temperature change (that is increase or decrease) can be interpreted to show that students believed "no heat was evolved" (that is only temperature increase). By contrast, the two possibilities (evolved and absorbed) are reported by Vidyapati and Seetharamappa (1995). Correspondingly, the difficulty description given above allows for either alternative. Due to the narrowness of the research probes and the questionable interpretation by Cros *et al.* there needs to be more investigation into this conception and the difficulty can only be given a low classification of Level 2 or Emergent. In the interim, the propositional statement below indicates the knowledge which I have introduced to students though practical work with relatively concentrated solutions of 1 mol.dm^{-3}.

- The acid-base neutralization reaction will cause a temperature rise. (7.1.4)

7.4.2 Difficulty interpreting observations of neutralization reactions

7.4.2.1 Difficulty P18: Strong acids perform better than weak acids.

Several studies concerning conceptions of different aspects of the reaction of weak and strong acids suggest a student notion that strong acids outperform weak acids. In particular, various authors have claimed that students believe that, when compared with weak acids, strong acids will react faster, or require more of the other reactant, or produce more product or release more heat during the reaction (see Table 7.5 which follows). There were no studies on the corresponding conception for bases.

Table 7.5 Research information on conceptions of performance of strong and weak acids

Reported conception	Educational level of students	Research information published	Authors
The difference between a strong acid and a weak acid is that strong acids eat material away faster than a weak acid.	Grade 10	No details of interview protocol or quotations	Hand & Treagust (1988)
A weak acid cannot perform in any way as well as a strong acid.	After 1 year university	No details of interview protocol, unsubstantiated interpretation	Cros *et al.*(1988)
More hydrogen gas is displaced from a strong acid.	Grade 12	Interview protocol given Student quotation given	Ross & Munby (1991)
Strength of acid or base is "how powerful or reactive the substance was"	Grade 10	Interview protocol given but no quotations	Sheppard (2006)
The strong electrolyte requires more moles for its neutralization ...because we have a strong acid and a strong base.	Grade 12	Matched pair of MCQ's with open-ended justification of choice given but no quotations	Demerouti *et al.* (2004)

The summary in Table 7.5 shows that the research has been thinly reported, for instance only Ross and Munby (1991) give student quotations such as: "a strong acid...reacts more greatly with other substances than a weak acid" to substantiate their claims. Moreover, Cros *et al.* (1986) do not report investigating other aspects of the reaction besides heat of reaction (see Difficulty P17 above), and show no further evidence for the broad generalisation about all aspects of the reaction which they give. However, their description is borne out by the other research and suggests the commonalty across these other reports, so I used it for the description given above. Classification of the difficulty remains at a low level of 2, or Emergent, because of the thinly reported research. Further research could illuminate what aspects of the performance of weak acids students have in mind or whether they are confusing the concepts of rate of reaction and amount of products (Banerjee, 1991). Provisionally, the conceptions reported above map onto propositional knowledge with a common theme of clarifying that weak acids are not different to strong acids in terms of amount of product or energy released.

- Acid or base strength depends on the chemical nature of the acid or base (8.1).
- All neutralization reactions produce the same heat of reaction (based on Arrhenius, 1912). (7.2.4.1)
- The different heat of reaction measured for weak acids is due to the extent of dissociation of molecules (based on Arrhenius, 1912). (7.2.4.2)
- For monoprotic acids, the rate of reaction for a weak acid (or base) will be less than from an equally concentrated strong acid (or base) (7.1.5), although the amount of product produced will be the same (7.1.6)
- For acid-base titrations indicators are chosen so that the end-point of a titration is also the equivalence point. (7.1.3.2) In principle, equivalent amounts react completely (7.1.3.1)

7.4.3 Difficulties with the nature of reactions in acid-base chemistry

The conceptions discussed in this section represent student difficulties in explaining the nature of a chemical reaction. Some of the difficulties reflect conceptions about fundamental principles in chemistry and for this reason, it is inappropriate to classify them only in the acid-base context.

7.4.3.1 Difficulty P19: Neutralization is mixing, not a chemical reaction.

The conception described above had been shown by Sheppard (2006) where 37.5% of the Grade 10 students held the idea that a neutralization reaction was a physical mixing rather than a chemical reaction due to interaction between particles. These students could neither name the new product nor give any equations; furthermore, they made particulate drawings showing unreacted chemical species. Nakhleh and Krajcik (1993) report a similar conception. The evidence in the two reports above, for the acid-base context, comes from students towards the end of high school but Talanquer (2008) reports the persistence of such naïve understanding of chemical reactions even after a semester of university chemistry. Consequently, the propositional statements concerning chemical reactions that were given earlier for P11 (see Section 7.3.1.5 e.g.: “When acidic substances react with carbonates, carbon dioxide is produced") have been subtly rephrased, as given below, to indicate that a mutual reaction between two substances produces the new substance. Because the difficulty is not unique to acid-base chemistry, it is inappropriate to classify the difficulty only in that context.

- Neutralization is a process whereby acids and bases react chemically to produce new substances. (7.1)
- Acids and carbonates react chemically to produce carbon dioxide. (2.1.1.6.2)
- Acids and some metals react chemically to produce a salt and hydrogen. (2.1.1.7)
- Acids and basic oxides react chemically, but produce no gases except water vapour. (2.1.1.6.1)

7.4.3.2 Difficulty P20: Acid-base reactions are additive

Sheppard (2006) reports a conception in which some students "described the formation of new products by the addition of an acid species to a base species". Moreover, students' drawings of sub-microscopic representations frequently showed base particles simply attached to acid particles. Nakhleh and Krajcik (1993) identified similar conceptions from student interviews. Furthermore, in the light of Talanquer's (2008) research, the difficulty is probably closely aligned to students using an additive, rather than an emergent framework. In such a case, students conceive the properties of the reactants to be the sum of the properties of the reactants, rather than new emergent properties. Accordingly, the difficulty is not classified only in the acid-base context here. The following propositional knowledge from Nakhleh & Krajcik (1993) is nevertheless useful:

- Neutralization is a double decomposition (or metathesis) reaction. (7.1.1)

The following discussion shows two sub-difficulties that arise from the difficulty which are particular to acid-base chemistry.

7.4.3.3 Sub-Difficulty P20.1: Indicators are necessary for or assist with neutralization

Within an additive framework for chemical reactions students will not accept the production of new substances with new properties, as might be detected by means of indicators. Instead they assign another role to indicators, which is that they assist with neutralization. This conception has been shown among junior secondary students (Botton, 1995), senior secondary students (Nakhleh & Krajcik, 1994) and pre-service teachers (Bradley & Mosimege, 1998). The consistency behind the three reports and corroborations from Demircioğlu *et al*. (2005) together allow me to classify the difficulty at Level 4, so it is now Established. These students may have been taught that an indicator is a weak acid or base (McNaught & Wilkinson, 1997), which in molecular or ionic form shows a different colour (Szabadváry, 1964). If this is the case, students also need to know that, in practice, negligible amounts of indicators are used. In this regard, Demircioğlu *et al*. (2005) report that the incidence of the difficulty reduced from 34 to 14% through conceptual conflict strategies and practical exercises. Based on the argument above, I include the following specific propositional statement:

- Indicators are substances which change colour at certain pH values. (6.1.2)
- Indicators are added in very small amounts, about 8 drops per 100 ml (Vogel, 1961). (6.1.1.2)

7.4.3.4 Sub-difficulty P20.2: Acid-base neutralization is neutralization of oppositely charged ions.

When investigating student conceptions of conjugate acid-base pairs, Schmidt (1995) found a common idea that neutralization involves positive and negative ionic charges neutralizing each other, as for example in the student quotation: “NH_4^+ has protons in excess and HSO_4^- has electrons in excess, that means it lacks protons. ... HSO_4^- and NH_4^+ seem to belong together, as if they somehow neutralized each other.” From his 1997 interpretation of the set of data, Schmidt argues: “Apparently they looked for positively and negatively charged ions ... assuming that they could somehow neutralize each other.” The research presented here is sufficient in itself to classify the difficulty description at Level 4 as it has been established in multiple chemical contexts through research among many different students groups in Germany. Schmidt’s description is consistent with later research into the same conception (Lin *et al.*, 2004; Drechsler & Schmidt, 2005b; Lin & Chiu, 2007; Furió-Más *et al.*, 2007). Brønsted (1923) appears to have already anticipated such a difficulty, as he clarifies: “Electric charge is irrelevant to the acid-base function.” Students, therefore, need to integrate the following propositional knowledge (see also Schmidt, 1991; Nakhleh & Krajcik, 1994; Ouertatani *et al.*, 2007):

- Electric charge is irrelevant to the acid-base function. (10.2.0.1)
- Arrhenius neutralization is the reaction between hydrogen ions and hydroxide ions (7.2) to produce water. (7.2.1)
- During neutralization reactions, cations from the base and anions from the acid form a salt. (7.2.2)
- Brønsted neutralization in water: H_3O^+ and OH^- ions tend to neutralize each other (7.3.3.1) which may be represented as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$. (10.3.2.1)

7.4.3.5 Difficulty P21: Acids are stronger than bases

Research shows that students believe bases are inherently weaker than acids, as shown by the following quotation from a Grade 11 student: "Bases are not strong" (Nakhleh & Krajcik, 1994). Very similar evidence is also reported by Ross and Munby (1991), Toplis (1998) and Sheppard (2006). All this evidence shows that students are sometimes unaware that both acids and bases can be strong. Consequently, without further analysis, the description of the difficulty given above can be classified at Level 3++ or Partially Established in more than one context. The conception maps directly to the following propositional knowledge:

- Acid or base strength depends on the chemical nature of the acid or base. (8.1) (Furió-Más *et al.,* 2007)
- Strong Arrhenius acids and bases are fully dissociated in solution. (8.2.2.1) (Ouertatani *et al.,* 2007)
- Strong Brønsted acids are good proton donors. (8.3.1) (Carr, 1984)
- Strong Brønsted bases are good proton acceptors. (8.3.2) (Carr, 1984)

A possible source of the difficulty is students' dichotomous view of acids and bases (See P4 in Section 7.2.2) and accordingly the difficulty is not given a separate classification. Alternatively, the source may lie within the teaching curriculum where the operational model defines an acid in terms of its ability to release hydrogen from particular metals; while a base is almost an adjunct with no character of its own – it is simply something that an acid tends to neutralize. In this regard, Solomonidou and Stavridou (2000) have shown that students think that substances have 'relative' properties and that the stronger substance would act on the weaker, without itself being affected. In the context of acids and bases, students may think that acids act on bases, rather than a reaction being a mutual interaction, as shown in the sub-difficulty below.

7.4.3.6 Sub-difficulty P21.1: The product of neutralization is acidic

As reported by Sheppard (2006) 10th grade students (12.5% incidence) considered acids as inherently more powerful than bases, leading always to an acidic product of neutralization reactions. The context he used was a titration between the strong acid HCl and the strong base NaOH where the product would be neutral. The difficulty maps to the following propositional knowledge:

- Neutralization reaction results in a solution that may be acidic, basic or neutral. (7.2.3)
- When equivalent amounts of a strong acid and an equally strong base react, the resulting solution will be neutral (7.2.3.1).

With evidence from only one controlled study, the sub-difficulty is described at Level 3. It needs to be confirmed in other chemical contexts, perhaps varying the relative strengths of acid and base.

7.4.3.7 Difficulty P22: Acid-base reactions proceed to completion

Two reports show the following similar student conceptions:

> "The base took over the acid" (Erduran, 2003).
>
> "In all neutralization reactions, acid and base consume each other completely" (Demircioğlu et al., 2005).

Is this in fact a problematic conception? Neutralization had originally meant that acid and base consumed each other so that neither acidic not basic property remained (Kauffman, 1988) and this remains acceptable today within an operational model (Drechsler & Schmidt, 2005b), as used for titrations (de Vos & Pilot, 2001). With modern knowledge of reversible reactions, Schmidt (1997) clarifies that because some H^+ and OH^- ions remain, "Acid and base do not consume each other completely; they react to a great extent." Moreover, in the Brønsted reaction scheme (Equation 3.9 in Figure 3.1, page 47) "acids and bases never disappear. An acid reacts with a base forming another acid and base" (Drechsler & Schmidt, 2005a). The following propositional knowledge reflects the argument above:

- For acid-base titrations, in principle, equivalent amounts react completely (7.1.3.1)
- Brønsted acid and base react to form Brønsted base and acid (7.3)
- Brønsted reactions are in principle reversible. (7.3.2)

Furthermore, a statement given for a previous difficulty (P20.2) is modified:

- Brønsted neutralization in water: H_3O^+ and OH^- ions tend to neutralize each other to a large extent, but not completely (7.3.3.1)

By reversing the propositional statements, the difficulty description as given above can be derived. However, there are certain problems with the two research reports on which this description is based. In the first report, Erduran (2003) makes no claims about the unanticipated student quotation representing a typical conception, and in the second Demircioğlu *et al.* (2005) do not substantiate their claim with qualitative data. Consequently, the difficulty can only be classified as Level 1, or Suspected. Future research needs to find out whether students carry the assumptions from an operational model through to equilibrium systems.

7.5 DIFFICULTIES WITH OTHER ACID-BASE REACTIONS

7.5.1 Difficulties with acid-base strength

7.5.1.1 Difficulty P23: Conjugate acid-base pairs are both strong or both weak.

While reporting on a study of students' ability to solve problem concerning chemical equilibrium, Camacho and Good (1989) give a quotation: "I think the weak acid produces the weak base." This statement maps to the propositional knowledge:

- Strength of acid-base conjugates is complementary. Stronger acids give rise to weaker conjugate bases and vice versa. (8.3.3) (Kolb, 1978). (8.3.3)

The difficulty can be described as in the heading above. Having arisen from only one source of data in one investigation, the difficulty is classified as Level 2, Emergent. A report on student difficulties with buffer systems (published more recently than the dates used to screen reports for the current analysis, see Table 4.1) confirms that tertiary students misunderstand the reciprocal acid-base nature of the conjugate pair (Orgill & Sutherland, 2008).

7.5.1.2 Difficulty P24: The Arrhenius model is for strong acids and the Brønsted model is for weak acids

When asking students multiple-choice items concerning the common ion effect, Demerouti *et al.* (2004) found that 13% of the Greek students surveyed chose the pair CH_3COOH/HCl as a non-example of a common ion system. The authors claimed this was "because they used the Arrhenius model for strong acids and the Brønsted-Lowry model for weak acids." However, no qualitative data was given to justify the claim, so it is classified at Level 2 or Emergent. The definitions for strength of acids in both models were already given under Difficulty P21 (see Section 7.4.3.5). These are now modified to show that both models contrast weak and strong acids.

- Strong Arrhenius acids or bases are fully dissociated in solution (8.2.2.1)
- Weak Arrhenius acids or bases are partially dissociated in solution (8.2.2.2)
- Stronger Brønsted acids are better proton donors than weaker Brønsted acids (8.3.1).

7.5.1.3 A salt is not a product – inappropriately reported as a misconception

Ross and Munby (1991) report as problematic an example of a student who was unable to identify one of the products of neutralization as a salt. This is similar to Bradley and Mosimege's (1998) assertion that students were incorrect if they did not choose the multiple-choice response: "Bases react with acids to form salts". It appears that for this concept both pairs of authors only had an operational model in mind, whereas many other items in Bradley and Mosimege's questionnaire frequently solicited knowledge of the theoretical Arrhenius and

Brønsted models rather than the operational model. Consequently, students would have been correct if they had applied the Arrhenius or Brønsted models, neither of which focuses on the formation of a salt. However neither report states overtly which model was expected in this case, and neither shows evidence of soliciting the students' frame of reference. Consequently, this is inappropriately reported as a misconception.

7.5.2 Difficulties with hydrolysis

When salt dissolves in water, the resulting solution may be non-neutral if either anion or cation undergoes hydrolysis. Difficulties recorded with this observation and with explanations of it in sub-microscopic terms are described next.

7.5.2.1 Difficulty P25 concerning macroscopic aspects of hydrolysis

Difficulties with predicting observations of neutrality (or otherwise) of salt solutions are shown by the student quotation: "Salt is neutral …because it is only a salt. If it was acidic or basic, then we should call [it] acid or base, not salt" (Pinarbasi, 2007) and quantitative data on student estimates of the pH of a solutions of sodium chloride and sodium ethanoate (Bradley & Mosimege, 1998). Both reports, however, give few details of the research. Consequently the descriptions are both classified at Level 2. Because of the scant research, I have considered these to be sub-difficulties concerning macroscopic observations of the neutrality (or otherwise) of aqueous solutions of salts, described as follows:

Difficulty P25.1: All salts have neutral aqueous solutions.

Difficulty P25.2: Sodium chloride does not have a neutral aqueous solution.

Further research may indicate that they are separate difficulties, if it shows two distinct patterns of students' thinking. The following research questions could be addressed: "Do students believe all salts have neutral solutions or only some of them?"and "On what basis do students make these predictions?" In the interim, I propose that practical exercises are used to introduce and develop the following propositional knowledge in students:

- Salts may have neutral or non-neutral solutions (5.1.3)
- NaCl forms a neutral aqueous solution. (5.1.2)
- Sodium ethanoate will have basic solution (5.1.3.1)

Research by Lin and Chiu (2007, p 793) showed that some students relied on statements concerning the strength of acid and base from which a salt was derived as an end in themselves to predict acid or base character of solutions of salts. The authors termed this student model, the "pithy formula model". The problem highlights the importance of such knowledge being taught in a meaningful way, otherwise students may memorize little more than a mnemonic. A meaningful explanation and prediction of hydrolysis effects demands understanding the system of ions in water and so necessitates propositional knowledge such as follows:

- Salts where ions are weaker Brønsted acids or bases than water will have neutral solutions (7.3.3.3.2.1)
- Salts where ions are stronger Brønsted acids than water will have acidic solutions. (7.3.3.3.2.2)
- Salts where ions are stronger bases than water will have basic solutions (7.3.3.3.2.3)

7.5.2.2 Difficulty P26: There is no acid-base reaction between water and the ions from a salt.

Two research reports give evidence of senior secondary student poor conceptual understanding of hydrolysis of ions at sub-microscopic level (see Table 7.6 below).

Table 7.6 Summary of research on sub-microscopic understanding of hydrolysis

Reported conceptions	**Incidence**	**Acceptable conception**	**Authors**
The whole salt undergoes hydrolysis.	45%	The ions undergo hydrolysis.	Furió-Más *et al.* (2007)
Students do not appear to know the cause of hydrolysis.	Not given	Hydrolysis is due to proton transfer between H_2O molecules and cations or anions	Furió-Más *et al.* (2007)
Aqueous solution of NH_4Cl would contain equal concentrations of H_3O^+ and OH^- ions and would consequently be neutral	27% to 28%	Greater concentration of H_3O^+, so solution is acidic	Schmidt (1991)
Aqueous solution of sodium acetate (ethanoate) would have equal concentration of H_3O^+ and OH^- ions and would consequently be neutral	25% to 28%	Greater concentration of OH^- ions, so solution is basic.	Schmidt (1991)

From this research it is evident that some students have a poor understanding of what is hydrolysed, how it is hydrolysed, the consequences of the hydrolysis on the ions in solution and hence the acid-base nature of the resultant solution. The difficulties in Table 7.6 map to the following propositional knowledge:

- Ionic compounds dissociate into cations and anions when they dissolve in water. (8.2.5.1)
- If ions are stronger Brønsted acids or bases than water, they will react with water molecules. (8.3.5)
- Hydrolysis is a chemical reaction between an ion or molecule and water (7.3.3.3.1)
- Brønsted acid-base reactions include hydrolysis. (7.3.3.3)
- Hydrolysis of anions or cations change the $[H_3O^+]$ and $[OH^-]$ (8.3.5.2)

It is difficult to encapsulate this difficulty in terms of the original research findings, but the propositional statements reveal the missing idea of a reaction between ions are water, leading to the description as given above. The difficulty has been shown in different German and Spanish cohorts, but the description given here needs to be confirmed, it is classified at Level 3+, being only partially established. Schmidt's data also shows that there was a close relationship between this conception and that for predicting neutrality (or otherwise) of the titrations between corresponding acids and bases, described as Difficulty P16 in Section 7.4.1.2.

7.6 SUMMARY AND DISCUSSION

From the analysis and synthesis in this chapter the following research findings concerning student difficulties with acid-base properties and reactions are evident:

- This chapter has identified twenty six individual difficulties (eight of which included sub-difficulties) concerning student conceptions of acid-base properties and reactions.
- The difficulties mapped to a total of 105 propositional statements, of which 11% had been introduced in the previous chapter.
- Eighteen of the difficulties involved macroscopic aspects of propositional knowledge. Of these, five difficulties implicated concepts which should also be understood on sub-microscopic or symbolic levels.
- The difficulties involving macroscopic understanding of acids and bases were identified among students at all educational levels – from junior secondary to tertiary – as well as pre-service and in-service teachers.
- A further eight difficulties mapped to proportional knowledge which was entirely theoretical, involving the nature of models or sub-microscopic and/or symbolic understanding. These difficulties were identified among senior secondary or tertiary students.
- Of the 26 difficulties and eight sub-difficulties described, eight are classified at Level 4, ten each at Levels 3 and 2, with nine still only at Level 1. There were two difficulties where a classification was inappropriate.

As in the previous chapter, the critical analysis performed in this aspect of the study has implications for teaching and learning. It also shows some challenges for future research. These are briefly discussed here as this important topic receives more extensive coverage in the final two chapters (9 and 10).

As in the previous chapter, the majority (nearly 70%) of the difficulties identified in this chapter confirm a lack of integration of empirical macroscopic observations into student conceptual frameworks. This is shown by 19 difficulties: P1 to P18 and P25. The evidence of such widespread difficulties, sometimes among senior students, suggests that chemistry education is becoming too theoretical and decontextualised. An advantage of teaching macroscopic observations through a study of acidic, basic and neutral household products could be to put chemistry in context, thereby relating it to everyday life and fostering more realistic understanding of safety issues (see P1 to P4). Furthermore, Furió-Más *et al*. (2005) found little evidence of textbooks incorporating macroscopic acid-base behaviour as an introduction to theoretical models, although "this is the problem that the Arrhenius and Brønsted theories must solve" (p 1353). It is therefore likely that students' theoretical ideas have not been well grounded in empirical evidence. For example, the explanation of hydrolysis should be driven by observations of trends in neutral and non-neutral solutions of salts. Both Difficulties P25 and P26 show this is not so, and students are learning facts and explanations in isolation. Furthermore difficulties with salts, (P15 and P25) could be due to an overemphasis on the theoretical Brønsted model, wherein salts as products of neutralization reactions are irrelevant.

Two categories of difficulties revealed in this chapter indicate problems with more fundamental chemistry than acids and bases. To be specific, classes of substances characterized by properties (P8 to P11) and the nature of the neutralization reaction (P19 to P22) can be seen as threshold concepts (Meyer & Land, 2006; Perkins (1999; 2006a; 2006b), in that they underpin, and are essential pre-requisites for learning higher level concepts. According to these authors threshold concepts are transformative and integrative, enabling a student to understand the subject discipline in a new and possibly irreversible way. Moreover, they are frequently troublesome. In particular, the notion of chemical change has been well documented as problematic (Johnson, 2002). However, according to Land *et al*. (2006), mastering threshold concepts takes time and repeated engagement with the concept from several perspectives. In this regard, de Vos and Verdonk's articles (1985a; 1985b; 1986; 1987a) show a sequence of conceptual conflict strategies appropriate for revisiting the idea of chemical change in a variety of contexts. It follows that the context of acid-base chemistry could also provide similar potentially transformative points, which curriculum planners can exploit in order to enhance understanding of the nature of chemical change. To this end, acid-base substances can be used to learn classification through characteristic properties, such as in the sequence used by Solomonidou and Stavridou (2000) and the new substances produced and the energy changes could be used to show chemical change.

More difficulties had been identified in this chapter than in the previous chapter. However, only about a quarter of difficulties have been thoroughly researched to give an established description at Level 4 which is a smaller proportion than was found in Chapter 6. Therefore, it appears that not only do students have more difficulties with acid-base properties than with the actual species, but also researchers have not gained as much insight into these difficulties. Research practitioners should, once again, take note of difficulties where further research is needed. For example, there is very little known about how students conceive the function of indicators (P13 and P14) or about the conception that acid and base consume each other (P22). Both these difficulties are merely suspected but have considerable impact on future learning. Difficulties with emerging descriptions include the concept students have about heat of neutralization. In this regard, the research for P17 is only vague because we do not know whether they are unaware of any energy changes, or whether they think heat is absorbed. Numerous other difficulties have Level 3 descriptions. These partially established difficulties need further studies, either to clarify or confirm descriptions in other contexts. In particular, the difficulty which students have identifying acidic and basic characteristics (P8) has been reported frequently, yet still has an extremely vague description. It remains to be seen whether the research community rises to the challenge of investigating these more abstract ideas of acid-base properties and processes, to achieve more Level 4 difficulty descriptions.

For the eight difficulties with Level 4 descriptions, further research merely showing the existence of this conception in yet another student population is now largely redundant. We know the conception, we know it exists; we need to change the focus of research, perhaps to a study like Chiu’s (2007) to show prevalence across ages. In this chapter Level 4 difficulty descriptions arose in two ways. Firstly, single sustained research projects could lead to Level 4 difficulty descriptions (P16 and P20.2) or, as in the previous chapter, the remainder of the Level 4 descriptions were derived through critical analysis of results combined from individual research projects. In some cases the aggregate of work on a difficulty has already been recognised. For example see Pinarbasi (2007) who cites work concerning the dangers (or lack thereof) generally attributed to acids and bases. However a valuable aspect of this critical analysis is its highlighting the combined evidence leading to other previously unrecognised Level 4 descriptions seldom mentioned in literature reviews, such as Difficulty P20.1 concerning the idea of indicators assisting with neutralization. The critical analysis of research on difficulties continues in the next chapter where it will concern even more abstract concepts in acid-base chemistry.

CHAPTER 8

SYNTHESIS OF STUDENT DIFFICULTIES AND PROPOSITIONAL KNOWLEDGE REGARDING TERMINOLOGY AND SYMBOLISM IN ACID-BASE CHEMISTRY

8.1 INTRODUCTION

This chapter is the third and final chapter presenting the synthesis of descriptions of student difficulties from the literature. The chapter considers the Research Question 4 namely, "*What difficulties do students experience with terminology and symbolism in acid-base chemistry?*" To answer this question, it was necessary to address the following sub-questions:

4a. *What descriptions of difficulties with acid-base terminology and symbolism can be synthesised from the existing research data?*
4b. *How stable are these difficulty descriptions across different contexts?*
4c. *What statements of propositional knowledge are needed to address the difficulties with acid-base terminology and symbolism?*

Once again a table summarising the main results is given first. In Table 8.1 each difficulty description (derived by the method in Section 4.5) with its classification level (see criteria in Table 4.4, Section 4.5.5.2) is followed by the propositional knowledge to which it was mapped (see Section 4.6). The table is followed by the discussion of individual difficulties which fall into three sub-categories. On the surface, it may appear that some of the difficulties with technical terms and symbolic representations in acid-base chemistry overlap difficulties presented in the previous two chapters but it will be shown that they represent distinct difficulties with different sources. To amplify, the first results section presents difficulties where concept labels are the cause. The second section of results shows difficulties arising from chemistry symbolism while the final sub-category of difficulties concerns symbolic representations involved with qualitative aspects of acid-base chemistry. The three sub-categories of difficulties are therefore linked by being due to problems with symbolic representation, which may be linguistic, chemical or mathematical. As in the previous chapter, in order to avoid tedious repetition for the reader, where a difficulty description and propositional knowledge arose from a single mapping, only a brief analysis is given.

Table 8.1 Student difficulties with acid-base representations with propositional statements

Difficulty Number	Difficulty Descriptions (In Bold) linked to Propositional Statements (coded)	Difficulty Classification
R1	**Acid strength is acid concentration**	2
	Strong Arrhenius acids or bases are fully dissociated in water. (8.2.2.1)	
	Stronger Brønsted acids are better proton donors than weaker Brønsted acids. (8.3.1)	
	A more concentrated solution contains more solute for the same amount of solution. (1.2.0.1.1)	
R1.1	**Acid strength is shown by more hydrogen in a chemical formula**	1
	Compounds in which a molecule or formula unit releases more than one H^+ ion by dissociation or ionization will increase the $[H^+]$ (or $[H_3O^+]$) in solution accordingly. (8.2.2.1.2)	
R2	**Strong acids have strong bonds**	3+++
	An Arrhenius acid HA will dissociate as: $HA \rightleftharpoons H^+ + A^-$ (10.2.1.1)	
	K_a is an equilibrium constant showing how well an acid dissociates (Arrhenius model) (8.2.4)	
	K_a for an Arrhenius acid HA is given by $K_a = \frac{[H^+].[A^-]}{[HA]}$ (8.2.4.1)	
	A low value for K_a indicates minimal tendency for a molecular acid to dissociate/ ionize (8.2.4.1.1.2)	
	Arrhenius acids or bases that are fully dissociated in solution exist mostly as ions. (8.2.2.1.1)	
	Arrhenius acids and bases that are partially dissociated in solution exist mostly as molecules with a few ions. (8.2.2.2.1)	
	Strong Arrhenius acids are strong electrolytes (8.2.3.1)	
	Weak Arrhenius acids are weak electrolytes. (8.2.3.2)	
R3	**Acid-base conjugate pairs are reactant pairs.**	4
	In the general Brønsted reaction scheme: $acid_1 + base_2 \rightleftharpoons base_1 + acid_2$ (10.3)	
	Conjugate pairs are reactant /product pairs: $acid_1/base_1$ and $base_2/acid_2$ (10.3.1)	
	Formulae for acid-base conjugate pairs differ only by a proton, H^+ (10.3.1.1)	
R4	**Ionization and dissociation are not distinguished.**	2
	Arrhenius acids and bases dissociate into ions in aqueous solution (8.2.1.1)	
	Ionic compounds are composed of ions (cations and anions) (8.2.5)	
	Ionic compounds dissociate into cations and anions when they dissolve in water (8.2.5.1)	
	Brønsted acid-base reactions include ionization. (7.3.3.2)	
	The formation of one or more ions from neutral molecules is ionization. (7.3.3.2.2)	
	Ions are formed when Brønsted molecular acids and bases dissolve in polar molecular solvents, such as water (7.3.3.2.3)	
R5	**Dissociation is decomposition**	1
	Dissociation is the separation of the constituents of an ion pair. (8.2.1)	
	Decomposition is the breakdown of a single molecular entity (8.2.1.2.1)	
R6	**All formulae with hydrogen indicate acids.**	4
R6.1	**Bases have formulae with no hydrogen.**	n/a
	Arrhenius bases include NaOH, $Al(OH)_3$ and $Zn(OH)_2$ (3.2.2.1.1)	
	Brønsted bases: examples include the *molecules* H_2O, NH_3, PH_3 amines and *ions* OH^-, $HCOO^-$, CO_3^{2-}, HCO_3^-, HSO_4^-, SO_4^{2-}, HS^-, CN^- and S^{2-}(3.3.2.1)	
	Amines are organic bases with a functional group $-NH_2$ such as CH_3NH_2 (3.3.2.1.1.1)	
R7	**All formulae with an OH group indicate bases.**	4
	Alcohols have a functional group –OH (5.2.2) for example: CH_3OH and CH_3CH_2OH (5.2.2.1)	
	Arrhenius bases: examples do not include alcohols. (3.2.2.2.2)	
	Arrhenius acids: examples include HCl, H_3PO_4 (sometimes given as $H{=}P(OH)_3$) and carboxylic acids. (2.2.2.1.1)	
	Carboxylic acids are organic compounds with a functional group –COOH (2.2.2.1.2), for example: CH_3COOH and HCOOH (2.2.2.1.2.1)	

n/a: It is not appropriate to classify the difficulty only in the acid-base context.

Difficulty number	Difficulty Descriptions (In Bold) linked to Propositional Statements (coded)	Difficulty Classification
R8	**When an acid molecule dissociates it divides in two.** An Arrhenius diprotic acid dissociates in two stages (10.2.1.2) given by the equations: $H_2SO_4 \longrightarrow HSO_4^- + H^+$ (10.2.1.2.1) and $HSO_4^- \rightleftharpoons SO_4^{2-} + H^+$ (10.2.1.2.2) giving the overall equation as: $H_2SO_4 \rightleftharpoons SO_4^{2-} + 2H^+$ (10.2.1.2.3) A Brønsted diprotic acid ionizes in two stages (10.3.3) given by the equations: $H_2SO_4 + H_2O \longrightarrow HSO_4^- + H_3O^+$ (10.3.3.1) and $HSO_4^- + H_2O \rightleftharpoons SO_4^{2-} + H_3O^+$ (10.3.3.2)	2
R9	**The equation showing formulae for substances is suitable to explain neutralization reactions.** An equation with formulae describes the substances that are reactant and product (10.1) The formula equation for neutralization has the form: acid + base $\longrightarrow$ salt + water (10.1.1) Equations with ionic reactants and/or products explain the reaction (10.2) Arrhenius model: neutralization may be represented as $H^+ + OH^- \longrightarrow H_2O$ (10.2.1)	2
R10	**The general Brønsted reaction scheme shows neutralization.** The Brønsted general reaction scheme applies to many different types of reactions (7.3.3) including neutralization (7.3.3.1) In the Brønsted model, neutralization may be represented as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$ (10.3.2.1)	3+
R11	**Difficulty R11: $pH = -\log_{10}[H^+]$ suggests pH is directly proportional to $[H^+]$** pH is an alternative method of representing hydrogen ion concentration, $[H^+]$. (9.4.1.1) Approximate pH can be calculated from $pH = -\log_{10}[H^+]$ (9.4.3)	4
R12.1	**pH is a measure of acid strength.**	3
R12.2	**pH is a measure of base strength.** Solutions with pH 1 to 3 are described as strongly acidic. (9.3.1.1) Solutions with pH 4 to 6 are described as weakly acidic. (9.3.1.2) Neutral solutions have a pH of 7. (5.1.1) Solutions with pH 8 to 10 are described as weakly alkaline. (9.3.2.1) Solutions with pH greater than 13 are described as strongly alkaline. (9.3.2.2) pH of a solution depends on the concentrations $[H^+]$ and $[OH^-]$ (9.4.2)	2
R13	**Difficulty R13: The function $pH = -\log_{10}[H^+]$ has upper and lower limits** pH usually applies to dilute solutions. (9.4.3.4) When $[H^+] = 1.0$ mol.dm^{-3} pH is 0. (9.4.3.2.1) When $[OH^-] = 1.0$ mol.dm^{-3} pH is 14. (9.4.3.2.2)	3++
R14	**pH has discrete integer values.** pH measured with a pH meter gives continuous values. (9.2.3) pH calculations with ionic concentrations are accurate to ± 0.1. (9.4.3.3.1.1) pH calculations with ionic activities are accurate to ± 0.02. (9.4.3.3.1.2)	3+
R15.1	**$pH = -\log [H^+]$ means using $[H^+]$ only due to a strong acid**.	4
R15.2	**$pH = -\log [H^+]$ means using $[H^+]$ only due to a strong base**. pH calculations using $pH = -\log [H^+]$ need systematic considerations of all the equilibria taking place. (9.7.1) Water is present in aqueous solutions. (9.1.1) Arrhenius model: Water dissociates as $H_2O \rightleftharpoons H^+ + OH^-$ (9.6.1.1.) Brønsted model: Water ionizes as: $2H_2O \rightleftharpoons H_3O^+ + OH^-$ (9.6.1.2) There are always H^+ (or H_3O^+) and OH^- from dissociation (or ionization) of water (9.7.1.1) When acid or base concentration is very low (less than 10^{-8} mol.dm^{-3}), the acid/ base contributes insignificantly to the $[H^+]$ (or $[H_3O^+]$)/ $[OH^-]$ ions from the dissociation (or ionization) of water, and the latter has a greater effect on the pH. (9.7.2.3)	3

Difficulty number	Difficulty Descriptions (In Bold) linked to Propositional Statements (coded)	Difficulty Classification
R16	**Diprotic acids can be treated as monoprotic acids.** pH calculations using pH = –log [H^+] need systematic considerations of all the equilibria taking place. (9.7.1) An Arrhenius diprotic acid dissociates in two stages (10.2.1.2) given by the equations: $H_2SO_4 \rightarrow HSO_4^- + H^+$ (10.2.1.2.1) and $HSO_4^- \rightleftharpoons SO_4^{2-} + H^+$ (10.2.1.2.2) giving the overall equation as: $H_2SO_4 \rightleftharpoons SO_4^{2-} + 2H^+$ (10.2.1.2.3) A Brønsted diprotic acid ionizes in two stages (10.3.3) given by the equations: $H_2SO_4 + H_2O \rightarrow HSO_4^- + H_3O^+$ (10.3.3.1) and $HSO_4^- + H_2O \rightleftharpoons SO_4^{2-} + H_3O^+$ (10.3.3.2) Compounds in which a molecule or formula unit releases more than one H^+ ion by dissociation or ionization will increase the [H^+] (or [H_3O^+]) in solution accordingly. (8.2.2.1.2)	2
R17	**Neutral and pH = 7are equivalent at all temperatures.** The ion-product constant for water, K_w, is equilibrium constant. (9.6.2.1.2) given by $K_w = [H^+].[OH^-]$ or $[H_3O^+].[OH^-]$ (9.6.2.1.1) $K_w = 1.0 \times 10^{-14}$ mol.dm^{-3}, (9.6.3.1) only at 25°C. (9.6.3.1.1) Increasing temperature will increase K_w (9.6.3) As [H^+] increases the pH decreases.(9.4.2.1) pH will decrease with increasing temperature. (9.5.1) We usually quote pH at the standard temperature of 25°C. (9.5.2) For a neutral solution, $[H^+] = [OH^-] = \sqrt{K_w}$ (9.6.2.2) Neutral solutions have a pH of 7 (5.1.1)	3+

8.2 DIFFICULTIES WITH TECHNICAL LANGUAGE IN ACID-BASE CHEMISTRY

This section presents five instances where student conceptual difficulties arise from unfamiliarity with chemists' special terminology in an acid-base context.

8.2.1 Difficulties with the term 'strength'

8.2.1.1 Difficulty R1: Acid strength is acid concentration

Consistent descriptions of student confusion between acid *strength* and *concentration* of a solution have been reported from studies with junior secondary students (Botton, 1995) and senior secondary students (Hand, 1989; Demircioğlu *et al.*, 2005; Ouertatani *et al.*, 2007). Botton (1995) contends that the difficulty lies in confusion with layman language suggesting that students have not progressed beyond an everyday meaning (as a stronger taste of more concentrated cool drink) for acid strength. This contention is borne out by the other three reports above which indicate that further exposure to traditional reception learning seems effective in correcting this conception. Through such instruction, students are inducted into the correct scientific meaning of acid strength in a variety of contexts, according to the following propositional knowledge statements:

- Strong Arrhenius acids are fully dissociated in solution. (8.2.2.1) (Ouertatani *et al.*, 2007)

- Stronger Brønsted acids are better proton donors than weaker Brønsted acids. (8.3.1)
- A more concentrated solution contains more solute for the same amount of solution. (1.2.0.1.1)

Few qualitative details substantiating the claims are published in any of the reports, and as a result the difficulty is classified at Level 2 or Emergent. For both the main Difficulty R1 and the sub-difficulties which follow, there appears to be no research on a similar conception of strong bases.

8.2.1.2 Sub-difficulty R1.1: Acid strength is shown by more hydrogen in a chemical formula

A possible corollary to the confusion between strength and concentration arises with the chemical formulae for acids and bases, where *strong* is inappropriately associated with *more*. In particular, Lin and Chiu (2007) report the conception that the number of H atoms or OH groups in chemical formula is a criterion for determining acid-base strength of solutions, as in the student quotation: "it [sulfuric acid] has two H…it ionizes H, that is hydrogen ion, I think sulphuric (sic) acid ionizes more." With the scant details reported, the classification is only Level 2, or Emergent. If students believe that concentration means the same as acid strength, then it is possible to reason that a greater ionic concentration arises from an acid with formula such as H_2SO_4 than from HCl and hence the former is a stronger acid. Further open ended research is needed. In the interim, the corresponding propositional knowledge should include the following:

- Compounds in which a molecule or formula unit releases more than one H^+ ion by dissociation or ionization will increase the $[H^+]$ (or $[H_3O^+]$) in solution accordingly. (8.2.2.1.2)

8.2.1.3 Difficulty R2: Strong acids have strong bonds

A difficulty of confusing *strong acids* with *strong bonds* has been shown among undergraduate and post-graduate students, as well as faculty staff, by Smith and Metz (1996). This research involved interviews concerning multiple-choice options depicting sub-microscopic representations of ions and/or molecules for hydrochloric acid, HCl, (a strong acid) and hydrofluoric acid, HF, (a weak acid). These authors report on undergraduate students who thought that strong acids such as HCl "won't separate" and are "hard to dissociate". Concerning HF, they also report: "Many students believe that a weak acid is easily pulled apart due to weak bonds or weak attractions between the charged species". The authors describe the student conception as "A strong acid has a strong bond". The conclusion arising from two sources of data (the students' choice of diagram and the interview quotations) concerning two contrasting chemical contexts, HCl and HF, indicates a consistent difficulty. Similar corroborating evidence for the conception of strong acids has been reported among senior secondary students (Ouertatani *et al.,* 2007; Furió-Más *et al.,* 2007; Ross & Munby, 1991) which allows the difficulty to be classified at Level 3+++, Partially Established in more than one context. In this difficulty, students appear to not differentiate between bond strength and acid strength. Here students have not accommodated a further meaning for strength and simply superimpose the bond strength conception onto acid strength.

Acid strength is shown quantitatively by the dissociation constant K_a. However, a definition is only one aspect of conceptual knowledge (White & Gunstone, 1992; Herron, 1996) and in this regard, many novices have a poor taxonomic understanding of the constants such as K_c, K_a, K_b etc, sometimes not even recognizing them as all being equilibrium constants (Camacho & Good, 1989). Therefore, limiting propositional knowledge to definitions of strong and weak acids, as under Difficulty P21 (Section 7.4.3.5) or for the dissociation constant K_a will not sufficiently address the difficulty. In this regard, students also need to understand the significance of different values of the dissociation constant, K_a in terms of acid strength and the types of particles found in solutions of weak or strong acids. Furthermore, Furió-Más *et al.* (2005) emphasise the macroscopic evidence for acid-base strength in terms of the electrical conductivity of their solutions. These aspects are addressed with the following propositional statements:

- An Arrhenius acid HA, will dissociate as: $HA \rightleftharpoons H^+ + A^-$ (10.2.1.1)
- K_a is an equilibrium constant showing how well an acid dissociates (Arrhenius model) (8.2.4)
- K_a for an Arrhenius acid HA is given by $K_a = \frac{[H^+].[A^-]}{[HA]}$ (8.2.4.1)
- A low value for K_a indicates a minimal tendency for a molecular acid to dissociate/ ionize in water (Furió-Más et al., 2007). (8.2.4.1.1.2)
- Arrhenius acids or bases that are fully dissociated in solution exist mostly as ions (8.2.2.1.1)
- Arrhenius acids or bases that are partially dissociated in solution exist mostly as molecules with a few ions (8.2.2.2.1)
- Strong Arrhenius acids are strong electrolytes (8.2.3.1)
- Weak Arrhenius acids are weak electrolytes (8.2.3.2)

8.2.2 Difficulty with acid-base pairs

8.2.2.1 Difficulty R3: acid-base conjugate pairs are reactant pairs

Research has shown that students do not recognize *conjugate* acid-base pairs as *reactant-product* pairs; instead they believe them to be both reactants. In his research into this conception Schmidt (1995) built on earlier work (Sumfleth, 1987) and through a triangulated study he showed the consistency (over several chemical contexts and among many different student cohorts) of a conception, which he described as given above. This extensive research establishes the conception and allows classification of the difficulty as Level 4. Schmidt (1995) suggests that textbooks need to include discussion which distinguishes conjugate pairs from reactant pairs, because the term "acid-base pair" can apply to both, accordingly such propositional knowledge (Schmidt, 1995; 1997) needs to be made clear as follows:

- In the general Brønsted general reaction scheme: $\text{acid}_1 + \text{base}_2 \rightleftharpoons \text{base}_1 + \text{acid}_2$ (10.3)
- Conjugate pairs are reactant/product pairs: $\text{acid}_1/\text{base}_1$ and $\text{base}_2/\text{acid}_2$ (10.3.1)
- Formulae for acid-base conjugate pairs differ by a proton, H^+ (10.3.1.1)

8.2.3 Difficulties with ionization, dissociation and decomposition

8.2.3.1 Difficulty: R4: Ionization and dissociation are not distinguished

Grade 12 student conceptions investigated by Kousathana *et al.* (2005) through two multiple-choice items revealed two difficulties concerning ionization and dissociation. The first difficulty indicates that students knew the different processes occurring when molecular and ionic substances dissolved, but muddled the respective concept labels of ionization and dissociation. This is a linguistic rather than conceptual difficulty (Clerk & Rutherford, 2000; Taber, 2001c) which is perpetuated in chemistry writing (see Sections 3.3.2.3 and 3.3.3.4) and will not be considered further here. The conceptual difficulty reported by Kousathana *et al.* (2005) is that students confused the processes of *dissociation* and *ionization* that occur respectively when ionic and molecular compounds dissolve in water.

In this reported research, concerning ionic compounds, selection of the multiple-choice distractor: "Ions are created during the dissolution of ionic compounds" by over 10% of the Grade 12 students indicated that they did not understand that a solid ionic compound already contains ions, which water can release from a lattice structure. These students appear to have understood ionization in the context of molecular compounds but inappropriately transferred it to ionic compounds, and so not seen the need to extend their conceptual understanding to include a new concept, *ionization*. Besides knowledge of ionic bonding (which falls outside the scope of the current analysis) the appropriate propositional knowledge is based on the correct option in the multiple-choice item as follows (Kousathana *et al*., 2005).

- Ionic solids are composed of ions (cations and anions) (8.2.5)
- Ionic solids dissociate into cations and anions when they dissolve in water. (8.2.5.1)

As Cokelez *et al.* (2008) have found, students are easily misled by equations which they think depict NaOH as a molecule like HCl, such as: $NaOH(s) \rightarrow Na^{+}(aq) + OH^{-}(aq)$. Cokelez *et al.* indicate that the process could be more clearly represented as: $Na^{+}OH^{-}(s) \rightarrow Na^{+}(aq) + OH^{-}(aq)$. Consequently, the difficulty with dissociation and ionization may be found to originate from difficulties with the chemical symbolism, but further research is needed to verify this conjecture.

Kousathana *et al*. (2005) also show students confusion about molecular compounds. Almost 20% of the students chose the distractor: "ions are released during the dissolution of molecular compounds". In a similar vein, Chiu (2005) reports that secondary students in Taiwan "considered that the molecule always dissolved in a solution in ionic state", but gives no further details. Both studies show that students are using a conception of dissociation for the molecular compounds instead of ionization, showing they have not seen a need to absorb a new concept with new terminology for ionization. Again, appropriate propositional knowledge as given below is based on that from Kousathana *et al*. (2005):

- Ions are formed when molecular Brønsted acids or bases dissolve in polar molecular solvents, such as water. (7.3.3.2.3)

As explained in Sections 3.3.2.3 and 3.3.3.4, a notion of 'dissociation' for both ionic and molecular compounds was chosen for the Arrhenius model whereas ionization was chosen for the Brønsted model, so it is also necessary to signpost the appropriateness of the terms within each model, as indicated by propositional knowledge given below:

- Arrhenius acids and bases dissociate into ions in aqueous solution. (8.2.1.1)
- Brønsted acid-base reactions include ionization. (7.3.3.2)
- The formation of one or more ions from neutral molecules is ionization. (7.3.3.2.2)

Until more is known about the nature of the difficulty, that is about whether it is due to confusion between the two models or poor understanding of the difference between ionic and molecular compounds (Furió-Más *et al*., 2007) or perhaps the chemical symbolism mentioned above, there is only a vague description of the difficulty: *Ionization and dissociation are not distinguished* and so it must be given a low classification – Level 2 or Emergent. Further research making use of free-response probes is needed. However, Southway (pers.com) suggests that emphasis at high school should lie in what is in solution, rather than the model for the process by which it got there.

8.2.3.2 Difficulty R5: Dissociation is decomposition

From a national study in Taiwan, Chiu (2007) reports the conception: “[A] weak electrolyte exists as a molecule or ions in water because [a] weak electrolyte can just partially decompose” which was identified among 13% of junior secondary and 34% of senior secondary students. I was unable to interpret this statement in the context of the study because supporting data was not published in English. Consequently, I am not clear whether this is a language difficulty of simply mis-labelling dissociation as decomposition – or a conceptual difficulty of actually thinking dissociation was decomposition into different compounds. Furthermore, the problem might have arisen in translating the research into English. Therefore, at this stage the difficulty is classified as Level 1 or Suspected. The propositional knowledge from IUPAC (McNaught & Wilkinson, 1997) clarifies the two processes:

- Dissociation is the separation of the constituents of an ion pair. (8.2.1)
- Decomposition is the breakdown of a single molecular entity (8.2.1.2.1)

8.2.3.3 Summary of difficulties with acid-base terminology

In this section two categories of difficulties have been identified with respect to chemists’ acid-base terminology. In the first case students apparently presume that an old concept label (along with its meaning) is the same as that for a new concept, and hence they do not accommodate the new scientific concept. This is evident in the difficulties concerning acid strength (R1 and R2) and conjugate pairs (R3). The second category includes difficulties where two labels are used interchangeably for one muddled undifferentiated conception such as Difficulties R4 and R5 concerning dissociation, ionization and decomposition. For effective communication, students need to be inducted into chemists’ special terminology.

8.3 DIFFICULTIES WITH CHEMICAL FORMULAE AND EQUATIONS

This section will discuss two sub-categories of difficulties. The first sub-section includes difficulties that students experience with regard the formulae for acidic, basic and neutral substances. The second subsection shows the difficulties students have concerning formulae and equations representing acid-base reactions.

8.3.1 Difficulties with formulae for acids and bases

8.3.1.1 Difficulty R6: All formulae with hydrogen indicate acids

A considerable number of students in senior secondary and even tertiary education treat formulae very superficially (see Table 8.2 below). The same difficulty has been reported in a wide variety of chemical contexts, all concerning bases with hydrogen in the formula. The formulae investigated include that for phosphine, PH_3, (a typical Lewis base and a weak Brønsted base), ammonia, NH_3 (a typical Brønsted base), methylamine, CH_3NH_2 (a weak Brønsted base) and even sodium hydroxide, NaOH, (a prototypic Arrhenius base). All were identified to be acids by the students as in the following typical quotation concerning PH_3: "it contains hydrogens and, therefore, can provide $[H^+]$... in aqueous solution" (Zoller, 1996).

Table 8.2 Summary of research concerning formulae incorrectly classified as acids

Formula investigated	**Percentage students classifying compound as an acid**	**Educational level of students**	**Country of cohort**	**Author(s)**
PH_3	not applicable	Tertiary	Israel	Zoller (1996)
NH_3	42	Senior secondary	Spain	Furió-Más *et al.* (2007)
NH_3	55	Senior secondary	Tunisia	Ouertatani *et al.* (2007)
CH_3NH_2	55	Senior secondary	Spain	Furió-Más *et al.* (2007)
NaOH	24	Senior secondary	Spain	Furió-Más *et al.* (2007)
NaOH	10-15	Senior secondary	Tunisia	Ouertatani *et al.* (2007)

The evidence for this difficulty in Table 8.2 shows its widespread occurrence among students from different language groups in many parts of the world, and its high incidence cannot be ignored, for example up to 55% of senior secondary students thought ammonia was an acid. From this evidence and without further analysis, the difficulty can be described as: *All formulae with hydrogen indicate acids.* The difficulty description is applicable through all the chemical and educational contexts in the table, so it can be classified as Level 4 or Established. The student difficulty maps to propositional statements below, of which the first two were introduced in Chapter 6 and are modified to include examples investigated above:

- Arrhenius bases include NaOH, $Al(OH)_3$ and $Zn(OH)_2$ (3.2.2.1.1)
- Brønsted bases: examples include the molecules H_2O, NH_3, PH_3, amines and ions OH^-, $HCOO^-$, CO_3^{2-}, HCO_3^-, HSO_4^-, SO_4^{2-}, HS^-, CN^- and S^{2-}(3.3.2.1)
- Amines are organic bases with a functional group $-NH_2$ such as CH_3NH_2 (3.3.2.1.1.1)

8.3.1.2 Sub-Difficulty R6.1 Bases have formulae with no hydrogen

A corollary to Difficulty R6 concerns the notion that bases have no hydrogen. Nakhleh and Krajcik (1994) report a single student quote about bases having formulae with no hydrogen. With no further controlled research into the nature of the difficulty, it is classified as a Level 1 or Suspected difficulty. This difficulty could be due to confused thinking about Brønsted bases as proton acceptors and, therefore, maps to the same set of examples given as propositional statement 3.3.2.1 for R6 above. For this reason, it is not treated as a separate difficulty.

8.3.1.3 Difficulty R7: All formulae with an OH group indicate bases.

In the context of bases, students display the same superficial student reasoning as they did with respect to acids. The reasoning is typified by the following student quotation concerning CH_3OH: “an ionic substance and so the OH^- in the formula is a hydroxide ion” (Furió-Más *et al.*, 2007). As with the previous difficulty, evidence in support of this difficulty comes from a wide variety of sources in educational contexts worldwide, mostly concerning senior secondary students (see Table 8.3 below).

Table 8.3 Summary of research concerning formulae incorrectly classified as bases

Formula investigated	**Percentage students classifying compound as a base**	**Educational level of students**	**Country of cohort**	**Author(s)**
$O{=}P(OH)_3$	not applicable	Tertiary	Israel	Zoller (1996)
CH_3CH_2OH	26 – 33	Senior secondary	Tunisia	Ouertatani *et al.* (2007)
CH_3CH_2OH	27 & 29 respectively	Junior & Senior secondary	Taiwan	Chiu (2007)
CH_3OH	61	Senior secondary	Spain	Furió-Más *et al.* (2007)
CH_3COOH	2	Senior secondary	Greece	Kousathana *et al.* (2005)
CH_3COOH	27	Senior secondary	Spain	Furió-Más *et al.* (2007)

Compounds investigated were phosphoric acid (usually given with the formula H_3PO_4, but here represented as $O{=}P(OH)_3$), ethanol, CH_3CH_2OH, and methanol, CH_3OH, (alcohols, not bases) and ethanoic (commonly called acetic) acid which has a typical carboxylic acid group COOH. As with the previous difficulty, the evidence needs no further analysis to derive the difficulty description given above.

While the cause for this difficulty may lie with underlying knowledge of bonding (Furió-Más *et al.*, 2007), the propositional knowledge statements below, arising from the chemical examples above, are relevant in the acid-base context .

- Arrhenius acids: examples include HCl, H_3PO_4 (sometimes given as $O{=}P(OH)_3$) and carboxylic acids (2.2.2.1.1)

- Carboxylic acids are organic compounds with a functional group –COOH (2.2.2.1.2) for example: CH_3COOH, and HCOOH. (2.2.2.1.2.1)
- Arrhenius bases: examples do not include alcohols (3.2.2.2.2)
- Alcohols have the functional group –OH (5.2.2) for example: CH_3OH and CH_3CH_2OH (5.2.2.1)

Based on the many different chemistry contexts investigated, as well as the consistency in student responses, I could classify the difficulty as Established or at Level 4. With fairly high incidences of the difficulty, as with R6, it cannot be ignored when teaching. Moreover, all the evidence together, suggests further questions. However, frustratingly, no further information is available to explain for instance why junior secondary students in Taiwan outperform their senior secondary counterparts. Neither do we know whether the much lower incidence of the difficulty in the Greek cohort (2%) was a result of a particular teaching strategy or whether the Spanish students had yet not been taught about carboxylic acids. The evidence does, however, suggest some answers below to questions arising from other prior research.

Ye and Wells (1998) had also investigated student conceptions of chemical formulae through multiple-choice questions. For the stem: “The formulas for the most common organic bases end in…” they found that many students chose the distractor COOH from the other options: Cl^-, NH_2, and H_2O. The authors speculate that students linked the word ‘organic’ to the only choice that involved a carbon atom but did not show any data to substantiate this interpretation. In the light of the research shown above, it is more likely to have been an association of the OH group with bases, rather than the carbon atom which enticed the students. The rather glib interpretation from Ye and Wells illustrates the lack of insight gained through multiple-choice instruments if distractors are not based on prior, open-ended research.

8.3.1.4 Discussion of difficulties with formulae for acids and bases

The descriptions for difficulties R6 and R7 both appear to be linked by simplistic reasoning leading some researchers (e.g. Zoller, 1996; Lin & Chiu, 2007) to describe them as one difficulty. Should they in fact be considered as one difficulty? As described in the Methods chapter (Section 4.5) difficulties are considered separate if they have different causes, different educational implications or if they need to be addressed through different teaching strategies. An analysis of the two difficulty descriptions in the light of this reasoning follows next.

From the theoretical framework (see Section 3.3) for the three historical models considered here, all acids contain hydrogen, and all Arrhenius acids are also Brønsted acids, but not vice versa. By contrast, Brønsted bases and Arrhenius (or operational model) bases are mutually exclusive classifications. This means that an Arrhenius base cannot be a Brønsted base, and neither can a Brønsted base be an Arrhenius base. It thus follows that a student with Difficulty R6 who uses the heuristic: *All formulae with hydrogen indicate acids* will not necessarily have a misplaced idea of what constitutes an acid in any of the models, although they treat formulae superficially. However, the conception R7: *All formulae with OH indicate bases* suggests not only a simplistic way of looking at formulae, but a circumscribed conception of a base, allowing only the Arrhenius model. Thus, it is proposed that R6 and R7 should be seen as two separate difficulties.

Students could fruitfully add examples to the categories illustrated in Figure 8.1 which follows. This diagram shows that all of the Arrhenius acids such as HCl, H_2SO_4 and H_3PO_4 are also Brønsted acids, whereas bases which are common to both the Arrhenius and Brønsted models are seldom included in high school curricula (see Section 3.3.3.4). Furthermore there are some examples of that fall into acids and bases, these are amphoteric species.

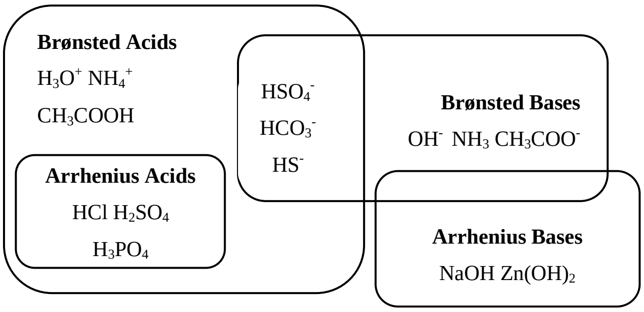

Figure 8.1 Classification of examples of acids and bases

8.3.2 Difficulties with formulae and equations in acid-base reactions

Nearly every research project considered so far has used a chemical context of monoprotic acids, typically HCl. From a project which included conceptions of polyprotic acids, simple chemical formulae for substances proved to be not so simple for students (Nakhleh & Krajcik, 1993). In this regard, Grade 12 students were often unable to write balanced formulae equations to represent the neutralization of phosphoric acid, H_3PO_4, by the base NaOH. To illustrate, one student gave the formula for sodium phosphate as $NaPO_4$ instead of Na_3PO_4. This is a difficulty with underlying chemistry of valency and ionic charge rather than being particular to acids and bases. Consequently, it is beyond the scope of the current synthesis. A difficulty that is particular to acid-base chemistry follows.

8.3.2.1 Difficulty R8: When an acid molecule dissociates it divides in two.

Furió-Más *et al.* (2007) investigated difficulties with dissociation of a diprotic acid through free-response questions, concerning the "complete ionic dissociation of H_2SO_4." Here, the authors do not publish their acceptable answers but the particular pairs which they reported as incorrect include: $H^+ + SO_4^{2-}$, and $H_2^+ + SO_4^{2-}$. From these examples, Furió-Más *et al.* (2007) describe the student mental model as: *When a molecule dissociates it divides in two.* These authors have not made their frame of reference clear (one or two stages or ionization to account for HSO_4^- (see propositional knowledge below). Furthermore, they appear to accept only the dissociation model for creating ions. Consequently, the interim difficulty description cannot be framed with certainty – it requires further, carefully reported research – so I classify it as Level 2, Emergent. Additional research needs less focused questions that do not restrict the students' scientific models, in order to discover whether the difficulty is due to the word 'dissociation' which is relevant only to the Arrhenius model, or some other cause. In the interim, the difficulty maps to propositional knowledge including both theoretical models.

- An Arrhenius diprotic acid dissociates in two stages (10.2.1.2) given by the equations:
- $H_2SO_4 \rightarrow HSO_4^- + H^+$ (10.2.1.2.1) and $HSO_4^- \rightleftharpoons SO_4^{2-} + H^+$ (10.2.1.2.2), giving the overall equation as: $H_2SO_4 \rightleftharpoons SO_4^{2-} + 2H^+$ (10.2.1.2.3)
- A diprotic Brønsted acid ionizes in two stages (10.3.3) given by the equations:
- $H_2SO_4 + H_2O \rightarrow HSO_4^- + H_3O^+$ (10.3.3.1) and $HSO_4^- + H_2O \rightleftharpoons SO_4^{2-} + H_3O^+$ (10.3.3.2)

8.3.2.2 Difficulty R9: The equation showing formulae for substances is suitable to explain neutralization reactions.

Drechsler and Schmidt (2005a) report an analysis of answers to school-leaving public examination multiple-choice questions where they found that instead of a net ionic equation, "students preferred reaction equations that name salt and water as a product of an acid-base reaction". Although not problematic among younger students, such conceptions which limit acid-base neutralization reactions to an operational model do not accommodate theoretical acid-base models, as could reasonably be expected of senior secondary students. Further research shows similar findings among students in Grades 10 and 11 (Ouertatani *et al.*, 2007) and Grade 12 (Furió-Más *et al.*, 2007), where the students apparently did not distinguish between the functions of the two types of equations, and preferred the apparently simpler one giving substances. Without further analysis, the difficulty can be described as: *The equation showing formulae for substances is suitable to explain neutralization reactions.* I only classify the difficulty at Level 2 because, despite evidence from three independent studies, there is little in the research to explain why students focus only on the one type of equation. As to possible causes, Ouertatani *et al. (2007)* give no backing for their suggestion that students may not have sufficient understanding of ionic reactions. A second possible cause is suggested by the seemingly indiscriminate use in advanced school textbooks of the two types of equations, with no explanation for a particular choice, as shown by Oversby (2000a). The difference between an equation to *describe* a reaction in terms of reactants and products and one to *explain* why the reaction is classed as neutralization represents the essential difference between an operational model and theoretical models. Consequently I put forward the following propositional knowledge as appropriate for this difficulty:

- An equation with formulae describes the substances that are reactants and products (10.1)
- The formula equation for neutralization reactions has the form: acid + base → salt + water (10.1.1)
- Equations with ionic reactants and/or products explain the reaction (10.2)
- Arrhenius model: neutralization is represented as: $H^+ + OH^- \rightleftharpoons H_2O$ (10.2.1)

In this difficulty students appear to ignore a later model, a different way they misunderstand models is shown in the next difficulty.

8.3.2.3 Difficulty R10: The general Brønsted reaction scheme shows neutralization.

The idea that students may superimpose parts of one acid-base model onto another, imagining that they model the same aspect is suggested in two reports. The student conceptions are best explained in terms of numbered equations representing the acid-base reaction, as shown in Figure 3.1 from the Theoretical Framework (see flip-out page 47). Firstly, Hand and Treagust (1988) report as a misconception found among Grade 10 students in Australia: “Neutralisation is the breakdown of an acid or something changing from an acid”. Such a student could have Brønsted’s reaction scheme in mind – thinking that equation 3.8 depicted an acid breaking down and that this was neutralization. Then Ross and Munby (1991) report a connection found on a student’s concept map: a base is the product of neutralization. Such a student could imagine that either of equations 3.8 and 3.9 concerning the Brønsted model showed neutralization. Use of either of these equations suggests that students are superimposing the general reaction scheme of the Brønsted model onto a neutralization reaction; that is, they are using the model inappropriately. These students should have rather applied equations in the form 3.1, 3.4 or 3.10 to aqueous neutralization. There is evidence to support my speculations, as follows.

Drechsler and Schmidt (2005b) give qualitative data from interviews showing that students did believe that the operational equation (1) and a Brønsted representation (4) both contained the same information. Indeed, both do have acid + base as reactants, which could confuse students, especially if they do not distinguish the acid-base models. For example, a student was confronted with the two equations:

$$HCl + NaOH \rightarrow NaCl + H_2O \quad \text{and} \quad acid_1 + base_2 \rightleftharpoons base_1 + acid_2$$

The student indicated the products and concluded: “salt and water are formed... there should be an acid and a base as well...perhaps you can identify NaCl as an acid...” From the same report, another student used NaOH instead of the ion OH^- as the proton acceptor. To accommodate this notion the student tried to write an equation with NaH_2O as the product. Drechsler and Schmidt categorize this difficulty as being due to students not understanding the appropriate contexts for each model, which is not a clear description. Instead, a clearer description could be obtained by mapping the difficulty to corresponding propositional knowledge statements, which in this case were:

- The Brønsted general reaction scheme applies to many different types of reaction. (7.3.3)
- Brønsted model, neutralization reactions can be represented as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$ (10.3.2.1)

Reversing these propositional statements then leads to the difficulty description: T*he general Brønsted reaction scheme shows neutralization.* This difficulty, suspected in two other contexts, is thus partially established through a further triangulated study (Drechsler & Schmidt, 2005b). Accordingly, it is classified at Level 3+. The difficulty is likely to be found among other student populations because Furió-Más *et al*. (2005) found evidence for this difficulty in 17% of the textbooks they analysed and 55% of teachers they surveyed indicated it was acceptable to explain neutralization using the Brønsted model. It follows that formal instruction could be the source of the difficulty. Further confirmation is also needed through studies in other chemical contexts.

8.3.2.4 Summary of difficulties with chemical symbolism

Difficulties with chemical symbolism show two categories of difficulties. Firstly students treat formulae in a simplistic way (R6, R7 and R8). The second category shows students do not understand the role of particular equations in different acid-base models. Both these categories indicate little understanding of the underlying chemical structure giving rise to acid or base properties and the formation of appropriate mental models to explain the behaviour. This is also implicated in the difficulties discussed in the next section.

8.4 DIFFICULTIES WITH SYMBOLIC AND MATHEMATICAL REPRESENTATIONS IN pH CALCULATIONS

The final sub-category of student difficulties concerns mathematical and symbolic representations, which are here limited to those concerning pH. This restriction arose because no research into difficulties with other quantitative acid-base topics arose in the initial search of publications. While a recently published report by Orgill and Sutherland (2008) concerns conceptions regarding buffer systems, this fell outside the date criterion for the screening process described in Section 4.4.1. Three quantitative aspects of pH have been investigated, specifically: its relationship to concentration, its supposed limits and finally pH arising from multiple equilibria.

8.4.1 Difficulties concerning pH and concentration

8.4.1.1 Difficulty R11: pH = – $\log_{10}[H^+]$ suggests pH is directly proportional to $[H^+]$

The conception that pH is directly related to concentration, as shown by the student quotation: "The most concentrated acid has the strongest pH" (Ouertatani *et al*., 2007) has also been shown by numerous other researchers (Camacho & Good, 1989; Zoller, 1996; Dhindsa, 2002; Sheppard, 2006) leading to the description above. The consistency of the difficulty across different contexts identified through different research instruments allows its classification at Level 4 or Established. Sheppard (2006) indicates that "few students understood the logarithmic nature of pH". Students' naïve literal interpretation of statements should be a concern for both educators and researchers. In this regard, propositional knowledge that could be misleading is given by both Nakhleh and Krajcik (1994) and Sheppard (2006) as: "pH is a measure of [this H^+ ion] concentration". Dhindsa (2002) puts forward a clearer meaning which I have used for the propositional knowledge below, and I have added the mathematical expression, as given in many textbooks.

- pH is an alternative method of representing hydrogen ion concentration, $[H^+]$. (9.4.1.1)
- Approximate pH can be calculated from pH = – $\log_{10}[H^+]$ (9.4.3)

8.4.1.2 Difficulty R12: pH is a measure of acid or base strength.

Four reports show that students make strong links between the strength of acids (or bases) and a particular fixed pH. This is evident from their concept maps which show links such as (words in italics are the concept labels given to the students): *Acids* can be *strong* like *hydrochloric acid,* which is *pH 1, Acids* can be *weak* like *citric acid,* which is *pH 4, Sodium hydroxide* is a *base,* which is *pH 14* (Botton (1995). Similar conceptions have been reported from senior secondary students (Ross & Munby, 1991) and undergraduates (Smith & Metz, 1996). Sheppard

(2006) elaborates that when Grade 10 students described pH as a measure of the ‘strength’ of an acid or base, they used ‘strength’ to mean: “how powerful or reactive a substance was” which suggest they associated pH with the tendency of an acid or base to be a proton donor or acceptor. Following a discussion of some of this research, Demerouti *et al*. (2004) and Oversby (2000b) clarify the difference between a weak acid (characterized by partial dissociation or ionization) and a weakly acidic solution (as measured by a pH of 4, 5 or 6). (Oversby’s suggestion of using the word ‘potent’ to distinguish a strong acid has yet to receive general acceptance.) As a result of this argument it is a misconception to assume that a particular pH characterizes acid-base strength. Students who do so may be unaware that pH will vary according to concentration, so a strong acid may have a pH close to 7 if it is in a dilute solution. Qualitative aspects of a concept such as pH should be taught in a way that forms a sound base for later studies of quantitative aspects (Hawkes, 1994). In this matter, Oversby (2000b) gives a qualitative interpretation of the pH scale, at an appropriate level for junior secondary students who have not yet formally encountered acid-base strength or ionic concentration, $[H^+]$, or pH calculations as summarised in the propositional knowledge below.

- Solutions with pH 1 to 3 are described as strongly acidic. (9.3.1.1)
- Solutions with pH 4 to 6 are described as weakly acidic. (9.3.1.2)
- Solutions with pH 7 are neutral. (5.1.1)
- Solutions with pH 8 to 10 are described as weakly alkaline. (9.3.2.1)
- Solutions with pH 11 to 13 are described as strongly alkaline. (9.3.2.2)
- pH of a solution depends on the concentrations $[H^+]$ and $[OH^-]$. (9.4.2)

The research described above shows the existence of the conception in four contexts but there are some problems. While Sheppard (2006) reports on a comprehensive study of the difficulty, only limited confirmation (that is single instances of the conception) comes from Ross and Munby (1991) and Smith and Metz (1996). Furthermore, only Botton (1995) reports investigating the student conception of strong bases, but in a model concept map he includes the difficulty described above as an *acceptable* proposition. Consequently, the difficulty description needs to be separated to show different classifications for difficulty descriptions concerning acids and bases, as follows:

Difficulty R12.1 pH is a measure of acid strength. (Level 3)

Difficulty R12.2 pH is a measure of base strength. (Level 2)

The implications of the difficulty for student conceptual development in the quantitative aspects of pH are important and so further research would be useful. Such research needs to find out whether students make a direct link between strength and pH, or if the conception follows from the idea that strength indicates concentration (Difficulty R1 in Section 8.2.1.1). Appropriate remedial strategies will depend on the source of the difficulty.

8.4.2 Difficulties concerning limits to pH

8.4.2.1 Difficulty R13: The function $pH = -\log_{10}[H^+]$ has upper and lower limits

The idea that there are upper and lower limits to the pH function has been reported by three researchers (see Table 8.4 below). Furthermore, Oversby (2002b) observed a student's confusion when the range was given inappropriately as 1 to 14, with neutral as 7 in the middle, because the student had calculated that 7.5 was midway between 1 and 14.

Table 8.4 Student conceptions of limits for pH

Lower limits	Upper limits	Educational level of students	Author
1	14	Tertiary	Zoller (1996)
0 or 0.01 or 1	9, 13 or 14	Pre-service teachers	Dhindsa (2002)
1	14	Teacher	Oversby (2000b)

When introducing the concept of pH, Sörenson (1909) noted that it would usually be a positive number, but in exceptional cases where $[H^+]$ was greater than 1 $mol.dm^{-3}$ it would have a negative value. In this regard, Oversby (2000b) clarifies that the practical limits are from –2 to 16. Consequently, the limits that students put on pH values are inappropriate, both theoretically and in practice. They indicate little understanding of the mathematical relationship shown by the symbols defining pH. This leads to the following propositional statements for the difficulty, as suggested by Dhindsa (2002):

- pH usually applies to dilute solutions. (9.4.3.4)
- When $[H^+] = 1.0\ mol.dm^{-3}$ pH is 0. (9.4.3.2.1)
- When $[OH^-] = 1.0\ mol.dm^{-3}$ pH is 14. (9.4.3.2.2)

Based on the common aspects across the reported research, I can describe the difficulty as: *the pH scale has upper and lower limits.* Having been identified in several contexts, I can classify the description at Level 3++. Further research may show whether students conceive the limits as theoretical or practical, what specific limits they tend to use, and perhaps where they see the midpoint of the scale.

8.4.2.2 Difficulty R14: pH has discrete integer values

As reported by Dhindsa (2002), “Students have difficulty in viewing continuity between numbers of pH”. These students gave the highest value of pH for an acid as 6 (2% prevalence) and the lowest value for a base as 8 (19% prevalence). He gives typical student reasoning as: “pH 7 is neutral, therefore, an acid has to have pH less than or equal to 6”. From this research, which used a written questionnaire and individual interviews with two cohorts of pre-service teachers in Brunei, I can classify the student conception as partially established in more than one context, i.e. Level 3+.

Further insight into the difficulty comes from research by Demerouti *et al*. (2004) which shows student responses (with justification of their choices), to pairs of complementary multiple-choice items. When asked about the pH of a 10^{-8} $mol.dm^{-3}$ solution of HCl, a few students responded with “7” instead of the authors’ preferred response: “just under 7” However, I cannot interpret this statement as evidence for the belief that pH is not continuous between numbers because I do not know the student frame of reference, and the multiple-choice format precluded other responses that were less than 7. Moreover, the incidence was small (2%). I have, however, used this research to rephrase the description of the difficulty more explicitly than that given by Dhindsa; it becomes: *pH has discrete integer values.* It remains to be confirmed whether this description will be stable in further contexts.

Concerning integer values, Oversby (2000a) notes that ‘weakly acidic’ is often taught as applying to pH values of 4, 5 or 6 rather than a range of values. The modern operational definition gives pH in terms of electrolytic measurements, such as with a pH meter (Hawkes, 1994; McNaught & Wilkinson, 1997) in which case it is a continuous variable. Although pH calculated by $-\log [H^+]$ may differ in the first decimal place from the measurement, this is near enough for most approximations, especially for dilute solution (Hawkes, 1994). Calculations using activity, instead of concentration are more accurate – having an uncertainty of ± 0.02 (McNaught & Wilkinson, 1997). This propositional knowledge could be presented for students as follows:

- pH measured with a pH meter gives continuous values. (9.2.3)
- pH calculations with concentrations are accurate to ± 0.1. (9.4.3.3.1.1)
- pH calculations with activities are accurate to ± 0.02. (9.4.3.3.1.2)

8.4.3 Difficulties concerning the effect of equilibrium systems on pH

Difficulties with chemical equilibrium have been extensively researched in general chemistry (see Gabel & Bunce, 1994). In this section, three difficulties specific to acid-base equilibria are discussed.

8.4.3.1 Difficulty R15: pH = –log [H$^+$] means using [H$^+$] only due to acid or base.

Three independent triangulated research studies have shown that students use the formula: pH = –log [H$^+$] in a simplistic algorithmic fashion, using only the acid concentration to calculate the pH of very dilute acidic solutions. Pinarbasi (2007) reports the following interview quotations, which show a student ignoring the relationship between acidity and pH in favour of an algorithm:

> Student A: ...according to pH = -log [H+], the pH [of 10^{-8} M HCl] will be 8.
> Interviewer: But, this is an acid solution, isn't it?
> Student A Yeah...but the equation says that its pH is 8
> Student B: If we added a large amount of water into this [10^{-5} M HCl] solution, we can make the pH of 8.

Similar reports to this quotation are summarised in Table 8.5 below. In all these studies students are shown to be applying the formula to calculate pH for both acidic (pH 8 and 10) and basic solutions (where students appear to use the pOH). In the case of very dilute solutions such as these, calculations should also take into account the self ionization of water (Skoog *et al.*, 1996). The pH values calculated by Skoog *et al.*'s method are given in the fifth column of the table. These are all extremely close to 7, and moreover are slightly below 7, for acidic solutions or just above 7 for basic solutions.

Table 8.5 Summary of research into student conceptions of pH for very dilute solutions

Concentration of acid/base in aqueous solution	Student conception of pH	Incidence	#Acceptable answer	*pH calculated	Education level of students	Authors
10^{-8} mol.dm^{-3} HCl	8	12%	Just below 7	6.98	Grade 12	Demerouti *et al.* (2004) Kousathana *et al.* (2005)
10^{-8} mol.dm^{-3} HCl	8	70%	Not given	6.98	Pre-service teachers	Pinarbasi (2007)
10^{-10} mol.dm^{-3} HCl	10	Not given	7	7.00	Tertiary	Watters & Watters (2006)
10^{-8} mol.dm^{-3} NaOH.	8	6%	Just above 7	7.02	Grade 12	Demerouti *et al.* (2004) Kousathana *et al.* (2005)

from authors

*By the present author using the method of Skoog *et al.* (1996)

All the studies investigated the conceptions of senior students who should have known about the existence of hydrogen (or hydronium) ions and hydroxide ions in water. The substantial proportion of students in Pinarbasi's study suggests this was possibly not so. Watters and Watters (2006) argue that their students favoured mathematical manipulations because of their fragmented conceptual understanding. In other words, students did not appear to integrate some essential propositional knowledge, which is given below.

- pH calculations using pH = –log [H^+] need systematic considerations of all the equilibria taking place (Kousathana *et al.,* 2005). (9.7.1)
- Water is present in aqueous solutions (Demerouti *et al.,* 2004). (9.1.1)
- There are always H^+ (or H_3O^+) and OH^- from water dissociation (or ionization). (9.7.1.1)
- Arrhenius model: Water dissociates as $H_2O \rightleftharpoons H^+ + OH^-$ (9.6.1.1)
- Brønsted model: Water ionizes as: $2H_2O \rightleftharpoons H_3O^+ + OH^-$ (9.6.1.2)

Ignoring the solvent may be part of a wider difficulty (Boo & Watson, 2001; Cokalez *et al.*, 2008), but the 'missing' propositional knowledge above suggests the difficulty as described below. The description is also limited to strong acids and bases because there appears to be no research on this conception in the context of weak acids or bases. With three triangulated studies giving consistent results, this difficulty can be considered as Established and classified at Level 4 in the chemical context of strong acids. However, with only one study on the corresponding conception for bases (albeit comprehensive, Demerouti *et al*. (2004) and Kousathana *et al.* (2005) report on the same data) the difficulty description needs to be separated to show different classification levels for conceptions of acidic and basic solutions. Accordingly, the difficulty descriptions are as follows:

Difficulty R15.1: pH = –log [H^+] means using [H^+] only due to a strong acid (Level 4)
Difficulty R15.2: pH = –log [H^+] means using [H^+] only due to strong base (Level 3)

The difficulty descriptions in their turn, now suggest further propositions to guide students as to when to take the self-ionization of water into account and when to ignore it. The method of Skoog *et al.* (1996) for calculations (assuming 100% dissociation of acid or base) gives rise to the guidelines below. The research evidence shows that students were unaware of the first statement below, while the second and third are included for completeness.

- When acid or base concentration is very low (less than 10^{-8} mol.dm^{-3}), the acid or base contributes insignificantly to the H^+ (or H_3O^+) / OH^- from the dissociation (or ionization) of water, which has greater effect on the pH. (9.7.2.3)

- When acid or base concentration is greater than 10^{-6} $mol.dm^{-3}$, the dissociation of water contributes insignificantly to the H^+ (or H_3O^+) / OH^- from the acid / base in solution and may be ignored in pH calculations. (9.7.2.1)
- When acid or base concentration is close to $10^{-7}$$mol.dm^{-3}$, the dissociation of water contributes significantly to the H^+ (or H_3O^+) / OH^- from the acid / base in solution, and both should be included in pH calculations. (9.7.2.2)

8.4.3.2 Difficulty R16: Formulae for diprotic acids can be treated as monoprotic acids

Demerouti *et al.* (2004) report that in the context of pH calculations, a number of Grade 12 students in Greece had "no clear understanding of the way that diprotic acids act". The difficulty has only a low classification of Level 2, Emergent, for two reasons. Firstly, the difficulty has a vague description as given above and secondly it was only investigated in one student cohort, and these had not actually studied equilibria involving polyprotic acids. Nevertheless, useful propositional knowledge might include the following statements:

- pH calculations using pH = –log [H+] need systematic considerations of all the equilibria taking place (Kousathana et al., 2005). (9.7.1)
- A diprotic Arrhenius acid dissociates in two stages (10.3.3) given by the equations: $H_2SO_4 \rightarrow HSO_4^- + H^+$ (10.2.1.2.1) and $HSO_4^- \rightleftharpoons SO_4^{2-} + H^+$ (10.2.1.2.2) giving the overall equation as: $H_2SO_4 \rightleftharpoons SO_4^{2-} + 2H^+$ (10.2.1.2.3)
- A diprotic Brønsted acid ionizes in two stages (10.3.3) given by the equations: $H_2SO_4 + H_2O \rightarrow HSO_4^- + H_3O^+$ (10.3.3.1) and $HSO_4^- + H_2O \rightleftharpoons SO_4^{2-} + H_3O^+$ (10.3.3.2)
- Compounds in which a molecule or formula unit releases more than one H^+ ion by dissociation or ionization will increase the $[H^+]$ (or $[H_3O^+]$) in solution accordingly. (8.2.2.1.2)

8.4.3.3 Difficulty R17: Neutral and pH = 7 are equivalent at all temperatures

In modern terms, the neutrality of a solution depends on equal hydrogen and hydroxide ion concentrations. The pH of such as solution would be 7 at 25^{o}C, but it would decrease with increasing temperature. The temperature dependence of pH is due to the degree of ionization of water increasing with increasing temperature, thereby increasing the concentration of hydrogen ions which in turn decreases the pH (Dhindsa, 2002, see Section 3.3.6).

Two independent research projects have report very similar results from investigating pre-service teachers' difficulties with the conception of the temperature dependence of pH (see Table 8.6 below).

Table 8.6 Summary of some research into conceptions of temperature effect on pH

Student conception of neutrality	Incidence	Authors
Neutral solution has a pH = 7	75%	Dhindsa (2002)
pH other than 7 means water is contaminated.	2%	Dhindsa (2002)
Neutral solution has a pH = 7	63%	Pinarbasi (2007)

Both authors above show corroborating evidence that, for a neutral solution, students accepted no other pH except 7. A few students (2%) believed this could only happen if the solution was contaminated (Dhindsa, 2002). Alternatively students thought a pH of 7 was the cause rather than the result of neutrality, as shown by the extract from an interview given below (Pinarbasi, 2007).

> Student: I know that pure water is neither basic nor acidic, it is neutral. To be neutral, the pH should be 7... yeah I said, if water has a pH of 7, it is neutral.
>
> Interviewer: OK, What would you say about the pH of pure water at different temperatures?
>
> Student: ...must be the same. It is 7...
>
> Interviewer: ...should water have different degrees of dissociation at different temperatures?
>
> Student: I don't think so. At any temperature, water would dissociate so that the concentrations of H^+ and OH^- will be the same, 10^{-7} M.
>
> Interviewer: Why do you think this is so?
>
> Student: Because, in order for water to be neutral, its pH must be 7.

The description of the difficulty given in the heading is suggested by the way these students inextricably link the two aspects: *Neutral* and *pH = 7* as being equivalent irrespective of temperature. These two independent projects each complement and corroborate the data from the other, which allows a classification of the difficulty description at Level 3+ because it is partially established and has been shown in more than one context. Subsequent research may lead to a more exact description, or perhaps there is more than one difficulty concerning ionic concentrations. Further research should be carried out among students who have been taught about the temperature dependence of K_w and pH, to verify whether the connection between these two concepts have been integrated into students' propositional hierarchy. These concepts had been adequately covered in typical textbooks for A-level and first year university according to Dhindsa (2002) and he recommends that the standard condition of 25°C be stressed, even in the junior grades. By contrast Pinarbasi gives an example from a university level textbook that ignores the standard conditions for pH, and he would like greater emphasis on the ionic product, K_w, is simply a particular example of an equilibrium constant. The propositional knowledge given below, which students appear to miss, is based on that given by Dhindsa (2002), Pinarbasi (2007) and an analytical chemistry text book by Skoog *et al*. (1996).

- The ion-product constant for water, K_w, is an equilibrium constant. (9.6.2.1.2) given by $K_w = [H^+].[OH^-]$ or $[H_3O^+].[OH^-]$ (9.6.2.1.1)
- $K_w = 1.0\times10^{-14}$ mol.dm^{-3}, (9.6.3.1) only at 25°C. (9.6.3.1.1)
- Increasing temperature will increase K_w (9.6.3)
- As $[H^+]$ increases the pH decreases.(9.4.2.1)
- pH will decrease with increasing temperature. (9.5.1)
- We usually quote pH at the standard temperature of 25°C. (9.5.2)
- For a neutral solution, $[H^+] = [OH^-] = \sqrt{K_w}$ (9.6.2.2)
- Neutral solutions have a pH of 7 (5.1.1)

It is also worth noting that in practice, distilled or deionized water is seldom neutral. Instead, it usually has a pH of 5.6 from being in contact with atmospheric carbon dioxide (Rayner-Canham, 1994).

8.5 SUMMARY AND DISCUSSION

The results presented in this chapter arose from Research Question 4 namely, "*What difficulties do students experience with terminology and symbolism in acid-base chemistry?*" To answer this question, it was necessary to address the following sub-questions:

4a. What descriptions of difficulties with acid-base terminology and symbolism can be synthesised from the existing research data?

4b. How stable are these difficulty descriptions across different contexts?

4c. What statements of propositional knowledge are needed to address the difficulties with acid-base terminology and symbolism?

In terms of these sub-questions, the main research findings in this chapter are:

- Seventeen difficulties can be described concerning representations in acid-base chemistry, of which three involved sub-difficulties.

- Of these difficulties, five each concern acid-base terminology and symbolic representations, with the remaining seven involving difficulties with quantitative aspects of pH.
- The difficulties described in this chapter were all identified among senior secondary or tertiary students.
- The stability of the difficulty descriptions varied. To be specific, only four difficulties (and one sub-difficulty) were established with a Level 4 description; five difficulties (and two sub-difficulties) were partially established at Level 3; five difficulties (and one sub-difficulty) were only classified as emergent or Level 2 and one difficulty (and two sub-difficulties) were merely suspected at Level 1.
- Difficulties with bases have been less extensively researched than those with acids.
- The 17 difficulties map to over 80 separate propositional statements, of which 85% were introduced for the first time when they mapped to difficulties in this chapter.
- The average of nearly five propositions per difficulty is greater than in the previous two chapters.

As in the previous chapters, the implications of these findings are discussed briefly here and more extensively in the following two chapters (9 and 10).

Some of the difficulties with representations used in acid-base chemistry identified in this chapter among senior secondary or tertiary students show these senior students retain simplistic or incorrect notions from their junior years, which then impede learning more complex or quantitative aspects of a concept. For example R17, concerning temperature dependence of pH, probably originates in earlier teaching when such details were ignored. Incorrect associations between pH and concentration and acid strength as in R11 and R12 have been identified among teachers and instructional material. Therefore, such difficulties have didactic origins, and textbook authors and teachers in junior classes need to be aware of these problems.

The seven difficulties identified here concerning quantitative aspects of pH belie Watters and Watters' (2006) claim that very little had been published on the topic. But their finding concerning the complexity of the topic is verified by the large number of propositional statements to which each difficulty is mapped. Not only is pH a counter intuitive concept, being an inverse relationship (Stavy & Tirosh, 2000), but the mathematics is challenging. In this regard, Potgieter *et al.*, (2008) found that university students could competently manipulate a logarithmic equation given in either purely algebraic or a typical chemistry format, but very few were able to interpret either form graphically, which suggests the students were unable to visualise the meaning of the mathematical symbolism. Furthermore difficulties R15 and R16 require advanced students to model several chemical equilibria occurring simultaneously, which is a task requiring considerable working memory (Badderly, 1986). However, the number of propositional statements should not be taken on face value as indicating the complexity or simplicity of a concept as is shown below.

Some of the difficulties in the sub-category concerning chemical symbolism appear to map to fewer propositional statements than for instance difficulties with terminology. For example Difficulty R10 (concerning chemical symbolism) maps to only three propositional statements whereas Difficulty R2 (concerning terminology) maps to eight propositions. This contrasts with Marais and Jordaan's (2000) assertion that symbolic language is the highest level of abstraction. Accordingly, if concepts involving symbolic representations are the most complex they could be expected to be represented by the greatest number of propositional statements. However the results here indicate otherwise. Therefore the propositional knowledge given here is most probably incomplete and in this way it represents only the minimum which students need to master. What is more, difficulties with chemical symbolism have been extensively reported in other chemical contexts (e.g. Yarroch, 1985; Nicoll, 2003; Treagust & Mamiala, 2003) indicating they are not specific to acid-base chemistry. Difficulties with a more fundamental origin could be expected to involve propositional knowledge beyond acid-base concepts and include general chemistry.

This chapter has exposed a large number of difficulties with more abstract aspects of acid-base chemistry. Each of these difficulties has been mapped to fairly extensive sets of propositional knowledge. The implications for teaching and learning of the complete set of propositional knowledge from this chapter, together with that from the previous two chapters, will be considered in the next chapter.

CHAPTER 9

THE SUITABILITY OF THE DERIVED PROPOSITIONAL KNOWLEDGE FOR TEACHING AND LEARNING ACID-BASE MODELS

9.1 INTRODUCTION

In the previous three chapters, critical analysis made use of propositional knowledge to hone descriptions of student difficulties (see method in Section 4.5) and in so doing, illuminated propositional knowledge in considerable detail (see Section 4.6). The focus changes in this chapter, as the whole set of propositional statements is first evaluated and then analysed, which entails, in part, developing a conceptual hierarchy. A composite list of propositional statements and hierarchical concept maps were built up simultaneously (see Section 4.7). The hierarchy is then used to cast light back onto the difficulties. By this analysis, an answer is sought for the fifth and final research question: *Do the set of propositional knowledge statements derived through analysis of student difficulties reflect appropriate knowledge for teaching and learning acid-base models?* This entailed answering two research sub-questions:

5a. How well do the propositional statements reflect curriculum models for acid-base chemistry?

5b. What are the implications of the propositional knowledge for teaching and learning acid-base chemistry?

Table 9.1 (pages 188 to 193) gives a composite list of all the propositional statements which are then followed by eleven concept maps (Figures 9.1 to 9.11). Both the table and the figures are given here in a flip-out format, so the reader may easily refer to them as they are discussed.

The propositional statements in Table 9.1 are arranged as a hierarchy of chemical concepts. Decimal codes for each propositional statement indicating the hierarchy (e.g. 3.4.2.1) are given in the left hand column and this is the same propositional statement code used in Chapters 6, 7 or 8. The hierarchy begins with propositional statements concerning general ideas about models (codes 1), then continues with species classed as acids (codes 2), bases (codes 3), amphoteric (codes 4), neutral or salts (codes 5). For each species, there are both definitions and examples appropriate to each model (operational, Arrhenius and Brønsted). The propositional statements then cover indicators (codes 6), acid-base reactions according to the three models (codes 7), acid-base strength (codes 8) according to the Arrhenius and Brønsted models, followed by pH (codes 9) and finally equations (codes 10). In this way the table covers all three models together but a practitioner can extract those propositions relating to a particular model relatively easily. The second column of the table shows the figure number(s) for the concept map(s) which include each proposition. The codes for the difficulties (e.g. S1, P5 or R10) from which the propositional statements were mapped are shown in the right hand column of the table. A few propositions show no difficulty code, for reasons which will be given in Section 9.2.1.

Each of the eleven concept maps depicts one theme in acid-base chemistry, starting with the overall relationships between acid-base models (Figure 9.1). This is followed by maps concerning acid-base species and acid-base reactions for each of the three models, namely operational (Figures 9.2 and 9.3) Arrhenius (Figures 9.4 and 9.5) and Brønsted (Figures 9.6 and 9.7). Then acid base strength is shown according to the latter two models (Figures 9.8 and 9.9). Lastly there are two concept maps for pH (Figures 9.10 and 9.11), showing firstly qualitative and then quantitative aspects of the concept. The hierarchical organisation of the concepts as shown by their decimal codes in Table 9.1 was more challenging than I had anticipated and in this regard the process of concept mapping was enormously helpful. I first made the maps with words, then allocated codes to them, then found whether there were already propositional statements which fitted the links or not, and whether they should be included on more than one map as will be discussed in Section 9.3.2.2.

All the concept maps have a similar format, with acids on the left hand side and equivalent concepts for bases on the right. Where a concept (e.g. strength) applies to both, it is usually aligned centrally, unless space constraints did not allow this (for example indicators on Figure 9.3). Concepts in rectangular boxes appear on more than one map (cross-links, see Section 9.3.2.2) with the remaining concepts depicted in ovals. Concepts boxes usually have white backgrounds, as shaded backgrounds have been reserved for concepts at critical nodes (see Section 9.3.2.1). Propositional links between concepts are described if these have not been shown as problematic. For brevity, links that were implicated in student difficulties are shown with only the decimal code for the propositional statement, together with code(s) for the difficulties. For example on Figure 9.2 the link with code 2.1.1.1 indicates the propositional statement 2.1.1.1 given in Table 9.1 as: *Acidic solutions have a pH less than 7* and this proposition was mapped from difficulties S1, P8, P12 and P20. Consequently, propositions in Table 9.1 should be consulted along with the concept maps. The links between concepts usually have uni-directional arrows to show which way the proposition should be interpreted. An equivalent relationship is shown with no arrows. For example on Figure 9.10 there is a link on the bottom left showing that *a pH of -2 is the practical minimum value*, this has no arrow because it has the same sense if read upwards as: *the practical minimum value for pH is -2*. But below this is the unidirectional link indicating: *the practical minimum is seldom achieved.*

Table 9.1 Composite List of all Propositional Statements

Code for Statement	Concept Map	Propositional Statement	Difficulties Implicated
		General ideas	
1.1	9.1	Operational and theoretical definitions are both necessary for scientific understanding.	S1
1.1.1	9.1 9.2	Operational definitions indicate how a physical quantity might be recognised or measured.	S1
1.1.2	9.1	Theoretical definitions show relationships between concepts	S1
1.1.3	9.1	Definitions vary according to different models	S3
1.1.3.1	9.1	Different models are useful in different contexts.	S3
1.1.3.3	9.1	Different theoretical models conceive acids and bases as substances or as particles	S2
		Operational model – general	
1.2	9.2	Acidic and basic substances have characteristic properties	S1
1.2.0.1	9.2 9.8	Properties in concentrated solutions may differ from those in dilute solutions	P1
1.2.0.1.1	9.2	A more concentrated solution contains more solute for the same amount of solution.	R1
1.2.0.2	9.2	Acids and bases have complementary properties.	P4
		Operational model acids – properties	
2.1	9.2	Acidic substances give acidic aqueous solutions.	S1
2.1.1.1	9.2	Acidic solutions have a pH less than 7.	S1 P8 P12 P20
2.1.1.2	9.2	Indicators have characteristic colours in acidic solutions	P8 P9
2.1.1.3	9.2	Weakly acidic solutions taste sour	S1 P5
2.1.1.3.1	9.2	Lemons taste sour.	P5
2.1.1.4	9.2	Acids can be corrosive and appear to ‘burn’ skin and eyes.	P1
2.1.1.4.1	9.2	Hydrochloric acid is usually corrosive.	
2.1.1.4.2	9.2	Weakly acidic solutions may be mildly corrosive and irritate eyes and skin	
2.1.1.4.3.1	9.2	Citric acid is irritating to eyes and skin.	P1
2.1.1.5.1	9.2	Acidic substances may smell ‘sharp’	P6
2.1.1.5.1.1	9.2	‘Sharp’ smelling gases may make you feel like choking.	P6
2.1.1.6.1	9.3	Acids and basic oxides or hydroxides react chemically but produce no gases except water vapour.	P11 P19
2.1.1.6.2	9.3	Acids and carbonates react chemically to also produce carbon dioxide.	S1 P11 P19
2.1.1.7	9.3	Acids and some metals react chemically to produce hydrogen.	P11 P19
		Operational model acids – examples	
2.1.2.1	9.2	Foods often contain acidic substances	S7 P2
2.1.2.1.1	9.2	Fruit, tea and milk contain acids	S7
2.1.2.2	9.2	CO_2 and SO_2 are acidic gases found in the atmosphere.	S2 S7
		Arrhenius acids – definition	
2.2.1	9.1 9.4 9.5 9.8	Arrhenius acids are substances that release hydrogen ions in aqueous solution.	S4
		Arrhenius acids – examples	
2.2.2.1.1	9.4	Arrhenius acids: examples include HCl. H_2SO_4, or H_3PO_4 (sometimes given as $O{=}P(OH)_3$) and carboxylic acids	S6 R7
2.2.2.1.2	9.4	Carboxylic acids are organic compounds with a functional group –COOH	R7
2.2.2.1.2.1	9.4	Carboxylic acids include CH_3COOH or HCOOH	R7
2.2.2.2.1	9.4	Some Brønsted acids are not Arrhenius acids	
2.2.2.2.1.1	9.4	Arrhenius acids: examples do not include water.	S2
		Brønsted acids –- definitions	
2.3.1.1	9.6	Brønsted model: particles (such as molecules or ions) are classified as acids when they donate a hydrogen ion, H^+, to a base	S2 S4 S6
2.3.1.2	9.7	When a Brønsted acid loses a proton it becomes the conjugate base	

Code for Statement	Concept Map	Propositional Statement	Difficulties Implicated
		Brønsted acids – examples	
2.3.2.1	9.4 9.6	Brønsted acids: examples include all Arrhenius acids	S2
2.3.2.2	9.6	Brønsted acids: examples include the water molecule H_2O and ions: HS^- or HCO_3^- and NH_4^+.	S2 S6
		Operational model bases – properties	
3.1	9.2	Basic substances (or alkalis) give basic (or alkaline) solutions.	S4
3.1.1.1	9.2	Basic solutions have a pH greater than 7.	S1 P8 P12
3.1.1.2	9.2	Indicators have characteristic colours in basic solutions	P8 P9
3.1.1.3	9.2	Weakly basic solutions taste bitter	P5
3.1.1.3.1	9.2	Soap tastes bitter	P5
3.1.1.4	9.2	Bases can be corrosive (or caustic) and appear to ‘burn’ skin and eyes.	P4
3.1.1.4.1.	9.2	Sodium hydroxide, potassium hydroxide and ammonia can be caustic or corrosive.	P4
3.1.1.4.1.1.	9.2	Sodium hydroxide and potassium hydroxide have the common name caustic soda and caustic potash	P4
3.1.1.4.2	9.2	Weakly basic solutions may feel soapy	P7
3.1.1.5.1	9.2	Ammonia has a strong pungent smell	P6
3.1.1.5.1.1	9.2	Urine smells of ammonia.	P6
		Operational model bases – examples	
3.1.2.1	9.2	Basic substances are found in cleaning materials such as oven cleaner, household ammonia, household bleach; washing soda (Na_2CO_3) and soap	S7 P3
3.1.2.1.1	9.2	Oven cleaner and drain cleaner contain basic substances such as NaOH	P4
3.1.2.2	9.2	Antacids are basic substances.	S7
3.1.2.2.1	9.2	Antacid: a medicine that prevents or corrects acidity in the stomach.	S7
3.1.2.3	9.2	Basic substances used in cooking include sodium bicarbonate	S7
3.1.2.4	9.2	Basic substances found in the laboratory include metal hydroxides such as limewater	S7
		Arrhenius bases – definitions	
3.2.1	9.4 9.5 9.8	Arrhenius bases are substances that release hydroxide ions in aqueous solution.	S4 S5
3.2.1.1	9.4	Alkali is an alternative term for Arrhenius bases	S5 P3
		Arrhenius bases – examples	
3.2.2.0	9.4	Arrhenius bases: examples are limited to substances containing OH groups.	S2
3.2.2.1.1	9.4	Arrhenius bases: examples include NaOH, $Al(OH)_3$, $Zn(OH)_2$ and ‘NH_4OH’	S2 S6 R6
3.2.2.2	9.4	Arrhenius bases examples do not include Brønsted bases	S5
3.2.2.2.1	9.4	Arrhenius bases examples do not include water and NH_3	S5
3.2.2.2.2	9.4	Arrhenius bases: examples do not include alcohols	S2 R7
		Brønsted bases – definitions	
3.3.1.1	9.6	Brønsted model: particles (such as molecules or ions) are classified as bases when they accept a proton (hydrogen ion) from an acid	S2 S4 S5 S6
		Brønsted bases – examples	
3.3.2.1	9.6	Brønsted bases: examples include the molecules H_2O, NH_3, amines and the ions OH^-, CO_3^{2-} or SO_4^{2-} or S^{2-}, HCO_3^- or HSO_4^- or HS^-	S2 S5 S6 R6
3.3.2.1.1.1	9.6	Amines are organic bases with a functional group $–NH_2$ such as CH_3NH_2	R6
3.3.2.2	9.4 9.6	Brønsted bases: examples do not include Arrhenius bases	S2 S5 R6
3.3.2.2.1	9.6	Brønsted bases: examples do not include NaOH	S2 S5
		Amphoteric species	
4.1	9.2 9.4 9.6	Amphoteric species are those that can behave both as an acid and a base	S6
4.1.1	9.6	Amphoteric properties depend upon the context in which the species is investigated.	S6
4.1.2	9.4	In aqueous solution, amphoteric hydroxides can form either hydrogen or hydroxide ions.	S6
4.2.1	9.4	Amphoteric substances examples include $Al(OH)_3$ or $Zn(OH)_2$	S6
		Operational model – neutral	
5.1	9.2	Neutral substances or solutions have neither acidic nor basic characteristics.	S4 S8 P4
5.1.1	9.2 9.10 9.11	Neutral solutions have a pH of 7.	S8 P12 R11 R17

Code for Statement	Concept Map	Propositional Statement	Difficulties Implicated
		Operational model – Salts	
5.1.2	9.2 9.3 9.9	NaCl forms a neutral aqueous solution.	S7 S9 P10 P25
5.1.3	9.3	Salts may have neutral or non-neutral solutions	P25
5.1.3.1	9.3 9.9	Sodium ethanoate has a basic solution	P25
		Arrhenius model – Neutral	
5.2	9.11	A neutral solution is one where $[H^+] = [OH^-]$	S10 P12
5.2.2	9.4	Alcohols have the functional group –OH	R7
5.2.2.1	9.4	Alcohols include CH_3OH and CH_3CH_2OH	R7
		Brønsted model – Neutral	
5.3	9.9	A neutral solution is one where $[H_3O^+] = [OH^-]$	S10
		Indicators	
6.1.1	9.3	Indicators are substances added to solutions of acids and bases	P9
6.1.1.2	9.3	Indicators are added in very small amounts, about 8 drops per 100 ml.	P20
6.1.2	9.3	Indicators are substances that change colour at certain pH values	P9 P13 P20
6.1.2.1	9.3	pH range over which indicators change colour is characteristic for each indicator.	P14
		ACID-BASE REACTION	
		Operational model – reaction	
7.1	9.3	Neutralization is a process whereby acidic and basic substances react chemically to produce new substances.	S2 P19
7.1.1	9.3	Neutralization is a double decomposition (or metathesis) reaction.	P20
7.1.2.1	9.3	Neutralization reactions produces a salt.	P19
7.1.2.1.1	9.3	The salt produced in neutralization reactions depends on the particular acid and base involved.	P15
7.1.2.1.3	9.3	Acetic (ethanoic) acid and sodium hydroxide will produce sodium acetate (ethanoate).	P15
7.1.2.2	9.3	In aqueous solutions, neutralization reactions produces water	S2 P19
7.1.3	9.3	Titrations use neutralization reactions between equivalent amounts of acids and bases.	P16
7.1.3.1	9.3	For acid-base titrations, in principle, equivalent amounts react completely.	P16 P18 P22
7.1.3.2	9.3	For titrations indicators are chosen so that the end-point of a titration is also the equivalence point.	P18
7.1.4	9.3	The acid-base neutralization reaction will cause a temperature increase	P17
		Arrhenius model – reaction	
7.2	9.5	Neutralization is the reaction between hydrogen ions and hydroxide ions	P20
7.2.1	9.5	Neutralization reactions produces water, H_2O	P20
7.2.2	9.5	During neutralization reactions, the cation from the base and the anion from the acid form a salt.	P15 P20
7.2.2.1	9.3	The solubility of salts depends on the particular ions involved.	P15
7.2.3	9.5	Neutralization reactions result in a solution that may be neutral, acidic, or basic.	P16 P21
7.2.3.1	9.5	When equivalent amounts of a strong acid and an equally strong base react, the resulting solution will be neutral.	P16 P21
7.2.3.2	9.5	When equivalent amounts of acid and base of unequal strength react, the resulting solution will not be neutral.	P16
7.2.3.2.1	9.5	Neutralization reactions between equivalent amounts of strong acids and weak bases result in acidic solutions.	
7.2.3.2.2	9.5	Neutralization reactions between equivalent amounts of weak acids and strong bases result in basic solutions.	P16
7.2.4.1	9.5	All neutralization reactions produce the same heat of reaction.	P18
7.2.4.2	9.5	The different heat of reaction measured for weak acids is due to the extent of dissociation of molecules.	P18
7.2.5	9.8	For monoprotic acids, the rate of reaction for a weak acid (or base) will be less than from an equally concentrated strong acid (or base).	P18

Code for Statement	Concept Map	Propositional Statement	Difficulties Implicated
7.2.6	9.8	For monoprotic acids, the amount of product produced from the same amounts of a weak and a strong acid will be the same.	P18
		Brønsted model – reaction	
7.3	9.7	Brønsted acid and base react to form Brønsted base and acid	P22
7.3.1	9.7	Brønsted acid-base reactions include non-aqueous systems.	
7.3.1.1	9.7	Non-aqueous examples: ammonia and hydrogen chloride	
7.3.2	9.7	Brønsted reactions are, in principle, reversible	P22
7.3.3	9.7	The Brønsted general reaction scheme applies to many different types of reactions	R10
7.3.3.1	9.7	Brønsted acid-base reactions include neutralization	R10
7.3.3.1.1	9.7	Brønsted neutralization in water is a reaction between H_3O^+ and OH^- ions	P16 P20 P22
7.3.3.1.2	9.7	Neutralization occurs to a large extent but not completely	P22
7.3.3.1.3	9.7	If neutralization reactions involve weak acid or base molecules there will at least two competing equilibria	P16
7.3.3.1.3.1	9.7	A stronger conjugate base in water will compete for H_3O^+ ions	P16
7.3.3.1.3.2	9.7	A stronger conjugate acid in water will compete for OH^- ions	
7.3.3.2	9.7	Brønsted acid-base reactions include ionization.	R4
7.3.3.2.2	9.7	The formation of one or more ions from neutral molecules is ionization.	R4
7.3.3.2.3	9.7	Ions are formed when molecular acids or bases dissolve in polar molecular solvents, such as water.	R4
7.3.3.3	9.7	Hydrolysis is a Brønsted acid-base reaction	P26
7.3.3.3.1	9.7	Hydrolysis is a chemical reaction of an ion or molecule with water	P26
7.3.3.3.2.1	9.9	Salts where ions are weaker Brønsted acids or bases than water will have neutral solutions.	P25
7.3.3.3.2.2	9.9	Salts where ions are stronger Brønsted acids than water will have acidic solutions.	P25
7.3.3.3.2.3	9.9	Salts where ions are stronger Brønsted bases than water will have basic solutions	P25
		Acid-base strength	
8.1	9.8	Acid or base strength depends on the chemical nature of the acid or base	P21 P18
8.2.1	9.8	Dissociation is the separation of the constituents of an ion pair.	R5
		Arrhenius acid-base strength	
8.2.1.1	9.5 9.8	Arrhenius acids and bases dissociate into ions in aqueous solution.	R4
8.2.1.2	9.8	Dissociation is not decomposition	
8.2.1.2.1	9.8	Decomposition is the breakdown of a single molecular entity	R5
8.2.2	9.8	Dissociation may occur fully or partially	
8.2.2.1	9.8	Strong Arrhenius acids or bases are fully dissociated in solution	P21 P24 R1
8.2.2.1.1	9.8	Arrhenius acids or bases that are fully dissociated in solution exist mostly as ions.	R2
8.2.2.1.2	9.8	Compounds in which a molecule or formula unit releases more than one H^+ ion by dissociation or ionization will increase the $[H^+]$ (or $[H_3O^+]$) in solution accordingly. (8.2.2.1.2)	R1 R16
8.2.2.2	9.8	Weak Arrhenius acids or bases are partially dissociated in solution	P24
8.2.2.2.1	9.8	Arrhenius acids and bases that are partially dissociated in solution exist mostly as molecules with a few ions.	R2
8.2.3	9.8	Arrhenius acid or base strength is measured by the conductivity of their solutions.	P13
8.2.3.1	9.8	Strong Arrhenius acids are strong electrolytes	R2
8.2.3.2	9.8	Weak Arrhenius acids are weak electrolytes.	R2
8.2.4	9.8	K_a is an equilibrium constant showing how well an acid dissociates (Arrhenius model)	R2
8.2.4.1	9.8	K_a for an acid HA is given by $K_a = \frac{[H^+].[A^-]}{[HA]}$ (Arrhenius model)	R2
8.2.4.1.1.1	9.8	Ka > 1, shows a strong acid with more ions than molecules in solution.	
8.2.4.1.1.2	9.8	A low value for Ka indicates minimal tendency for a molecular acid to ionize.	R2
8.2.5	9.8	Ionic solids are composed of ions (cations and anions)	R4
8.2.5.1	9.8	Ionic compounds dissociate into cations and anions when they dissolve in water.	R4 S1 P26

Code for Statement	Concept Map	Propositional Statement	Difficulties Implicated
8.2.5.1.1	9.8	In reality, few salts dissociate completely in water	S1
8.2.6.1	9.8	Lower concentration of ions results in a slower reaction rate	
8.2.6.1.1	9.8	A greater concentration of ions in solution will result in a greater reaction rate	
		Brønsted acid-base strength	
8.3.1	9.9	Stronger Brønsted acids are better proton donors than weaker Brønsted acids.	P21 R1 P24
8.3.2	9.9	Stronger Brønsted bases are better proton acceptors than weaker Brønsted bases.	P21
8.3.3	9.9	Strength9.8 of acid-base conjugates is complementary. Stronger acids give rise to weaker conjugate bases and vice versa.	P23
8.3.3.1	9.9	As a base, acetate ion, Ac^-, is stronger than its conjugate HAc is an acid.	P16
8.3.4	9.9	Ka is an equilibrium constant showing how well an acid ionizes (Brønsted model)	
8.3.4.1	9.9	Ka for an acid HA is given by: $K_a = \frac{[H_3O^+].[A^-]}{[HA]}$ (Brønsted model)	
8.3.5	9.9	If ions are stronger Brønsted acids or bases than water, they will react with water molecules.	P26
8.3.5.2	9.9	Hydrolysis of anion or cation causes a change in $[H_3O^+]$ and $[OH^-]$	P26
		pH	
9.1	9.10	pH can be found for any aqueous solution, including salts.	P10
9.1.1	9.11	Water is present in aqueous solutions.	R15
9.2.1	9.10	pH is an indirect practical scale.	P10 P12
9.2.2	9.10	pH is a scale of acidity and alkalinity.	P10 P12
9.2.3	9.10	pH measured with a pH meter gives continuous values.	R14
9.3.1	9.10	As solutions become more acidic, the pH decreases.	P4 P12
9.3.1.1	9.10	Solutions with pH less than 3 are described as strongly acidic.	R12
9.3.1.2	9.10	Solutions with pH 4 to 6 are described as weakly acidic.	R12
9.3.2	9.10	As solutions become more basic, the pH increases.	P4 P12
9.3.2.1	9.10	Solutions with pH 8 to 10 are described as weakly alkaline.	R12
9.3.2.2	9.10	Solutions with pH greater than 13 are described as strongly alkaline.	R12
9.4.1.1	9.10	pH is an alternative method of representing hydrogen ion concentration, $[H^+]$.	R11 P10 P12
9.4.2	9.11	pH of a solution depends on the concentrations $[H^+]$ and $[OH^-]$	R12
9.4.2.1	9.11	As $[H^+]$ increases the pH decreases.	P12 R17
9.4.2.2	9.11	As $[OH^-]$ increases the pH increases.	P12
9.4.3	9.11	Approximate pH can be calculated from $pH = -\log_{10}[H^+]$,	R11
9.4.3.1	9.11	$[H+] = 10^{-pH}$ mol.dm^{-3}	
9.4.3.2.1	9.11	When $[H^+] = 1.0$ mol.dm^{-3} pH is 0.	R13
9.4.3.2.2	9.11	When $[OH^-] = 1.0$ mol.dm^{-3} pH is 14.	R13
9.4.3.3.1.1	9.11	pH calculations with ionic concentrations are accurate to ± 0.1.	R14
9.4.3.3.1.2	9.11	pH calculations with ionic activities are accurate to ± 0.02.	R14
9.4.3.4	9.11	pH usually applies to dilute solutions.	R13
9.5.1	9.10 9.11	pH will decrease with increasing temperature.	R17
9.5.2	9.11	We usually measure pH at the standard temperature of 25 °C.	R17
9.6.1.1	9.5	Arrhenius model: Water dissociates as $H_2O \rightleftharpoons H^+ + OH^-$	R15
9.6.1.2	9.11	Brønsted model: Water ionizes as: $2H_2O \rightleftharpoons H_3O^+ + OH^-$	R15
9.6.2.1	9.11	Hydrogen ion concentration and hydroxide ion concentration are related by K_w.	P12
9.6.2.1.1	9.11	$K_w = [H^+].[OH^-]$ or $[H_3O^+].[OH^-]$	P12 R17
9.6.2.1.2	9.11	The ion-product constant for water, K_w, is an equilibrium constant.	P12 R17
9.6.2.2	9.11	For a neutral solution, $[H^+] = [OH^-] = \sqrt{K_w}$	R17
9.6.3	9.11	Increasing temperature will increases K_w	R17
9.6.3.1	9.11	$K_w = 1.0 \times 10^{-14}$	P12 R17

Code for Statement	Concept Map	Propositional Statement	Difficulties Implicated
9.6.3.1.1	9.11	$K_w = 1.0 \times 10^{-14}$ mol.dm^{-3}, only at 25 °C.	R17
9.7.1	9.11	pH calculations using pH = $-\log_{10}[H^+]$ need systematic considerations of all the equilibria taking place.	R15 R16
9.7.1.1	9.11	There are always H^+ (or H_3O^+) and OH^- from dissociation (or ionization) of water.	R15
9.7.2.1	9.11	When acid / base concentration is greater than 10^{-6} mol.dm^{-3}, the dissociation (or ionization) of water contributes insignificantly to the H^+ (or H_3O^+) / OH^- ions from the acid / base in solution, and may be ignored in pH calculations.	
9.7.2.2	9.11	When acid / base concentration is about 10^{-7}mol.dm^{-3}, the dissociation (or ionization) of water contributes significantly to the H^+ (or H_3O^+) / OH^- ions from the acid / base) in solution, and both should be included in pH calculations.	
9.7.2.3	9.11	When acid / base concentration is very low (less than 10^{-8} mol.dm^{-3}), the acid / base contributes insignificantly to the H^+ (or H_3O^+) / OH^- ions from the dissociation (or ionization) of water, and the latter has a greater effect on the pH.	R15
9.7.3	9.11	Diprotic acids dissociate/ionize in two stages, hydrogen/hydronium ions are produced in each stage. There are at least two equilibria to consider.	
		EQUATIONS	
		Equations – operational model	
10.1	9.3	An equation with formulae describes the substances which are reactants and products.	R9
10.1.1	9.3	The formula equation for neutralization reactions has the form acid + base $\rightarrow$ salt + water	R9
		Equations – theoretical models	
10.2	9.7	Equations with ionic reactants and / or products explain the reactions	S2 R9
10.2.0.1	9.7	Electric charge is irrelevant to the acid-base function	P20
		Equations – Arrhenius model	
10.2.1	9.5 9.9	Arrhenius model: neutralization reactions may be represented as: $H^+ + OH^- \rightleftharpoons H_2O$	R9
10.2.1.1	9.8	An Arrhenius acid HA will dissociate as: $HA \rightleftharpoons H^+ + A^-$	R2
10.2.1.2	9.8	An Arrhenius diprotic acid dissociates in two stages given by the equations	R16
10.2.1.2.1	9.8 9.11	$H_2SO_4 \rightarrow HSO_4^- + H^+$	R16
10.2.1.2.2	9.8 9.11	$HSO_4^- \rightleftharpoons SO_4^{2-} + H^+$	R16
10.2.1.2.3	9.11	Giving the overall equation as: $H_2SO_4 \rightleftharpoons SO_4^{2-} + 2H^+$	R16
		Equations – Brønsted model	
10.3	9.7	In the general Brønsted reaction scheme: $acid_1 + base_2 \rightleftharpoons base_1 + acid_2$ (10.3)	R3
10.3.1	9.7	Conjugate pairs are reactant /product pairs: $acid_1/base_1$ and $base_2/acid_2$ (10.3.1)	R3
10.3.1.1	9.7	Formulae for acid-base conjugate pairs differ by a proton, H^+	R3
10.3.0.1.2	9.7	acid $\rightarrow$ conjugate base + H^+	
10.3.0.1.3	9.7	base + $H^+ \rightarrow$ conjugate acid	
10.3.2	9.7	Non-aqueous example: $HCl + NH_3 \rightleftharpoons NH_4^+ + Cl^-$	
10.3.2.1	9.7	Brønsted model, neutralization reactions can be represented as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$	P16 P20 R10
10.3.3	9.7	A diprotic Brønsted acid ionizes in two stages given by the equations:	R16
10.3.3.1	9.7	$H_2SO_4 + H_2O \rightarrow HSO_4^- + H_3O^+$	R16
10.3.3.2	9.7	$HSO_4{–} + H_2O \rightleftharpoons SO_4^{2-} + H_3O^+$	R16
10.3.4.1	9.9	Acetate ions reaction with water may be shown as: $H_2O(l) + Ac^-(aq) \rightleftharpoons OH^-(aq) + HAc(aq)$	
10.3.4.2	9.7	Acetate ions reaction with hydronium ions as shown by: $H_3O^+(aq) + Ac^-(aq) \rightleftharpoons H_2O(l) + HAc(aq)$	P16

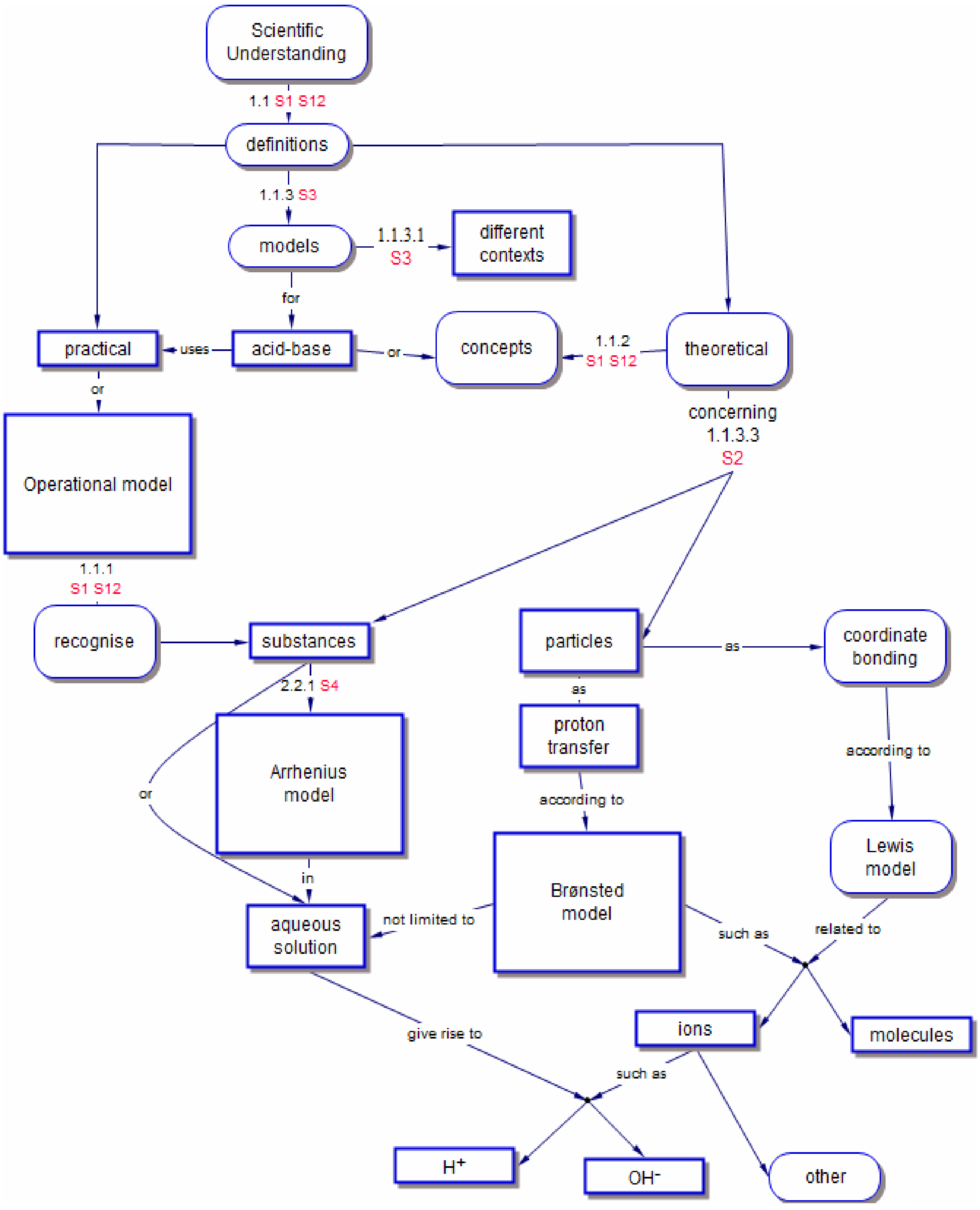

Figure 9.1 Concept map for Scientific Understanding

Key for Concept Maps Figures 9.1 to 9.11

concept — Concept also appears on other concept maps

concept — Concept appears only on this concept map

concept or concept — Concept has 3 or more incoming links

3.2.1 etc Code for propositional statement from Table 9.1

S3 P3 or R3 etc Code for difficulty from Table 6.1 7.1 or 8.1

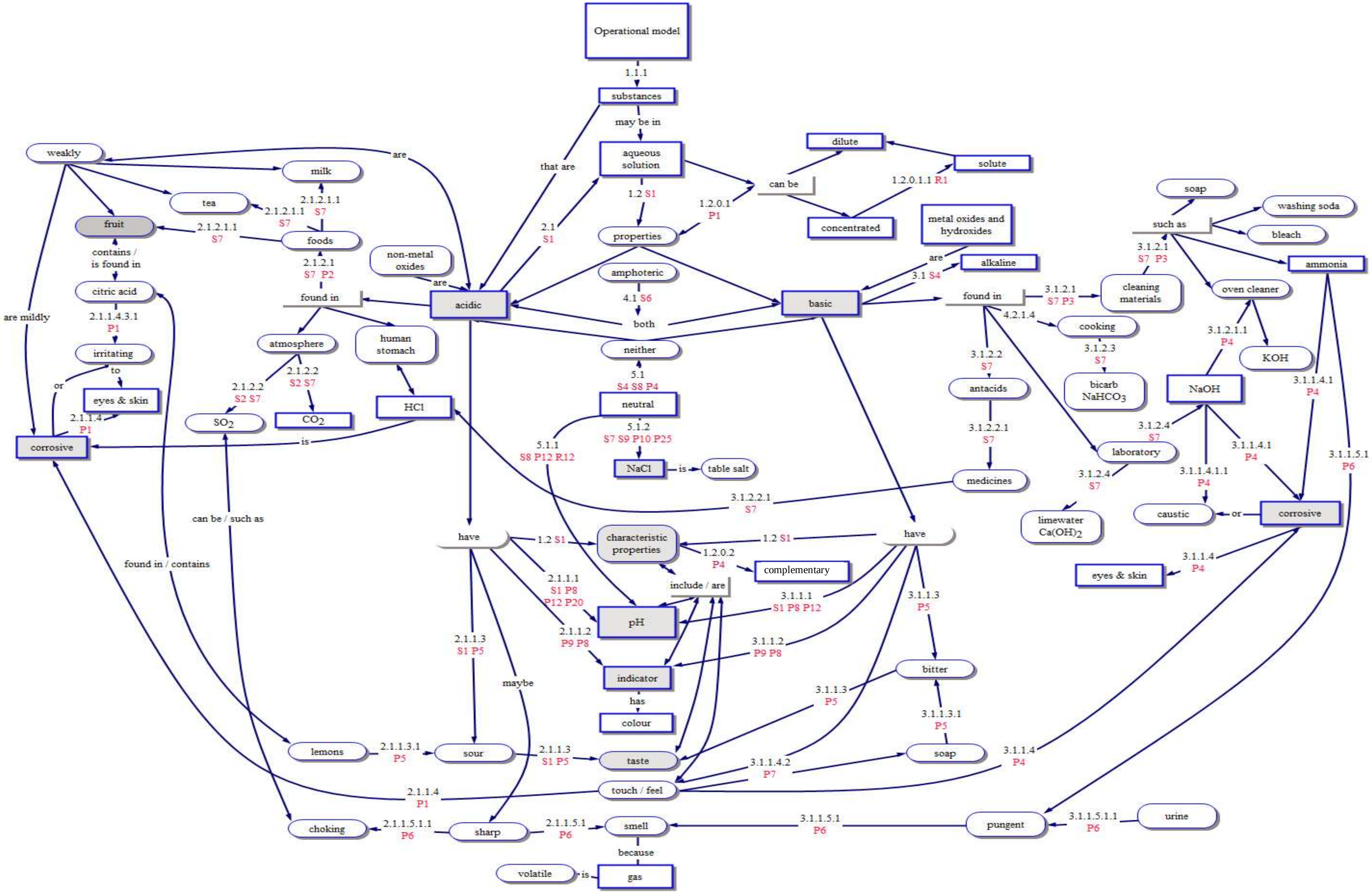

Figure 9.2 Concept map for Operational model of acid-base species

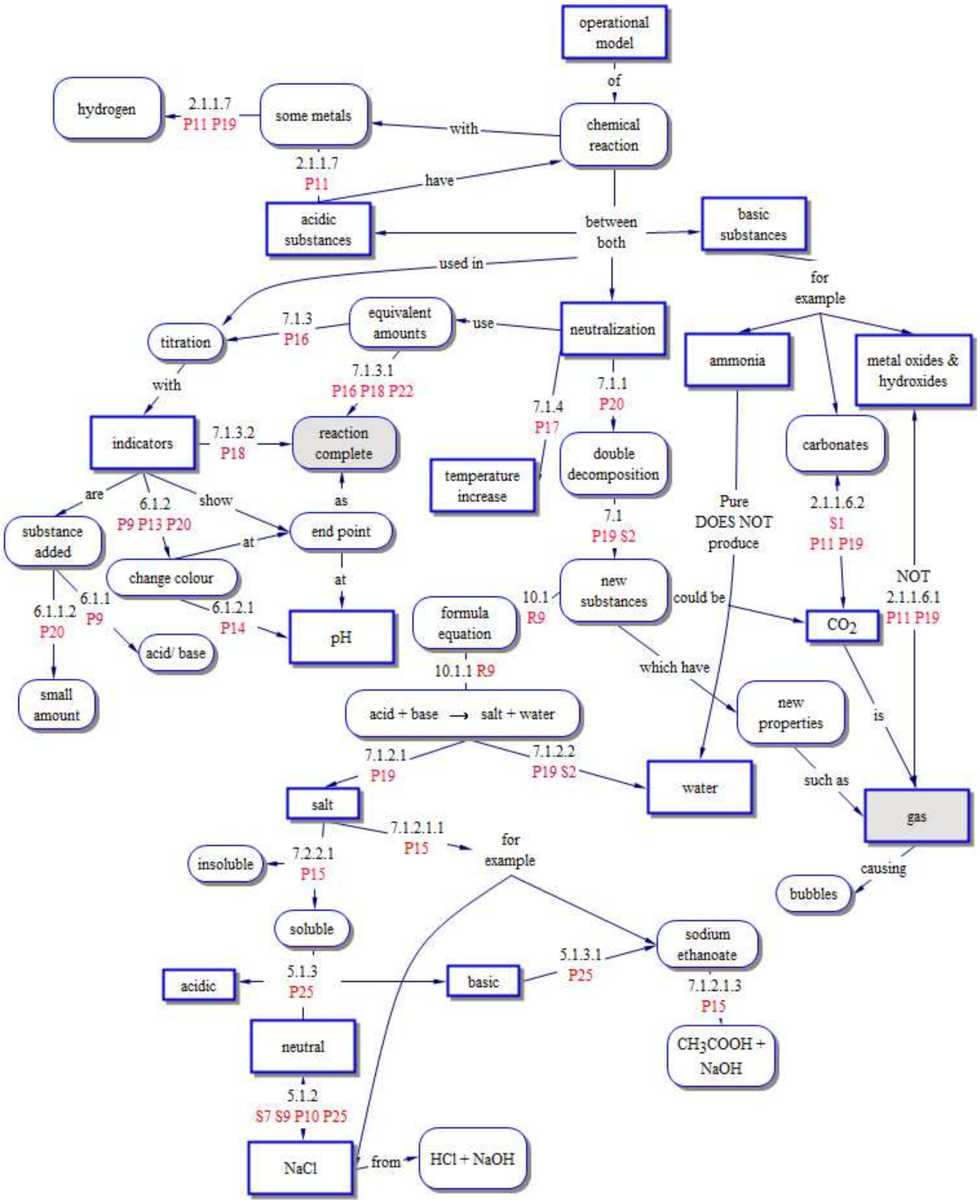

Figure 9.3 Concept map for Operational model of acid-base reactions

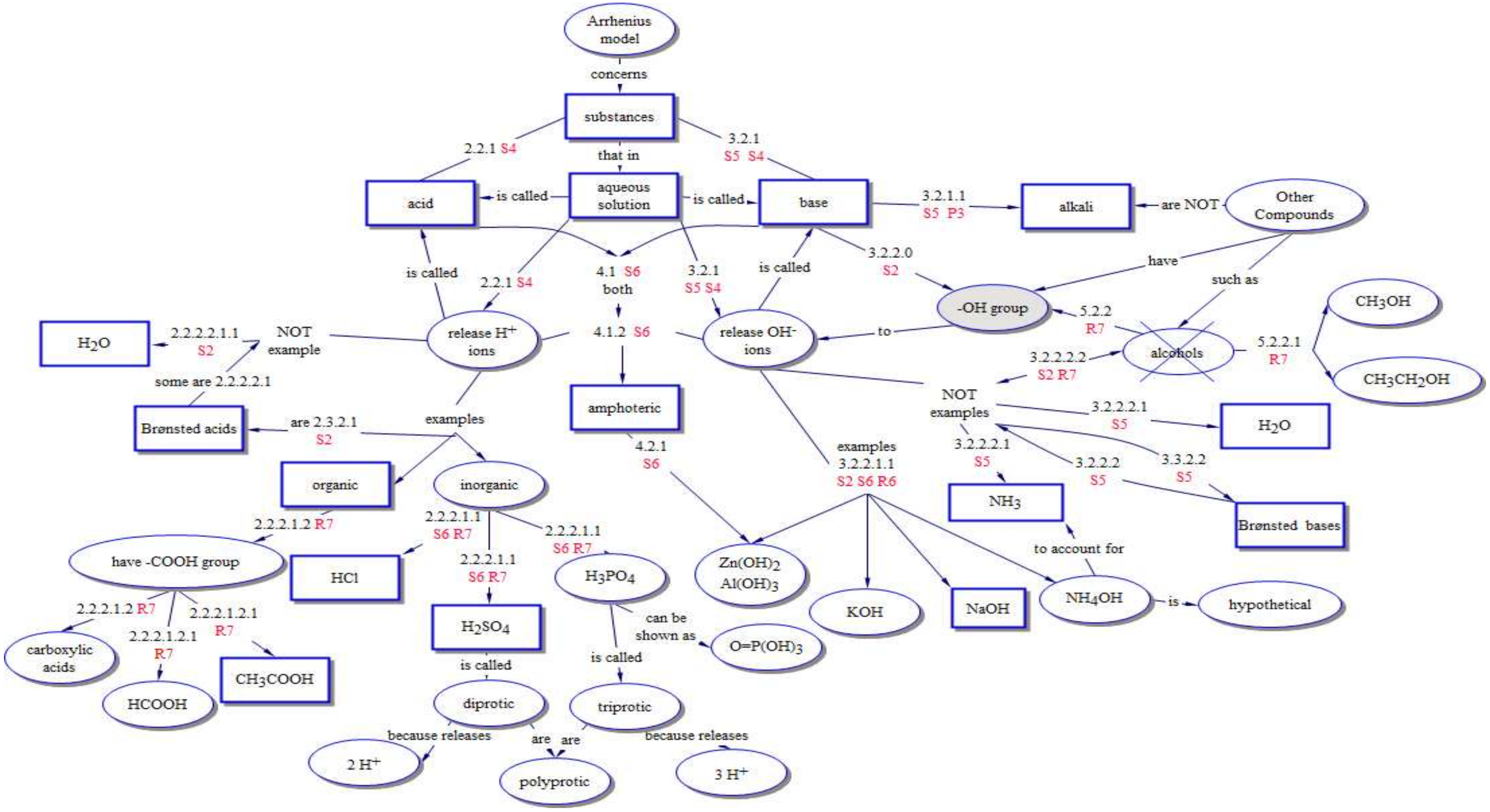

Figure 9.4 Concept map for Arrhenius model of acid-base species

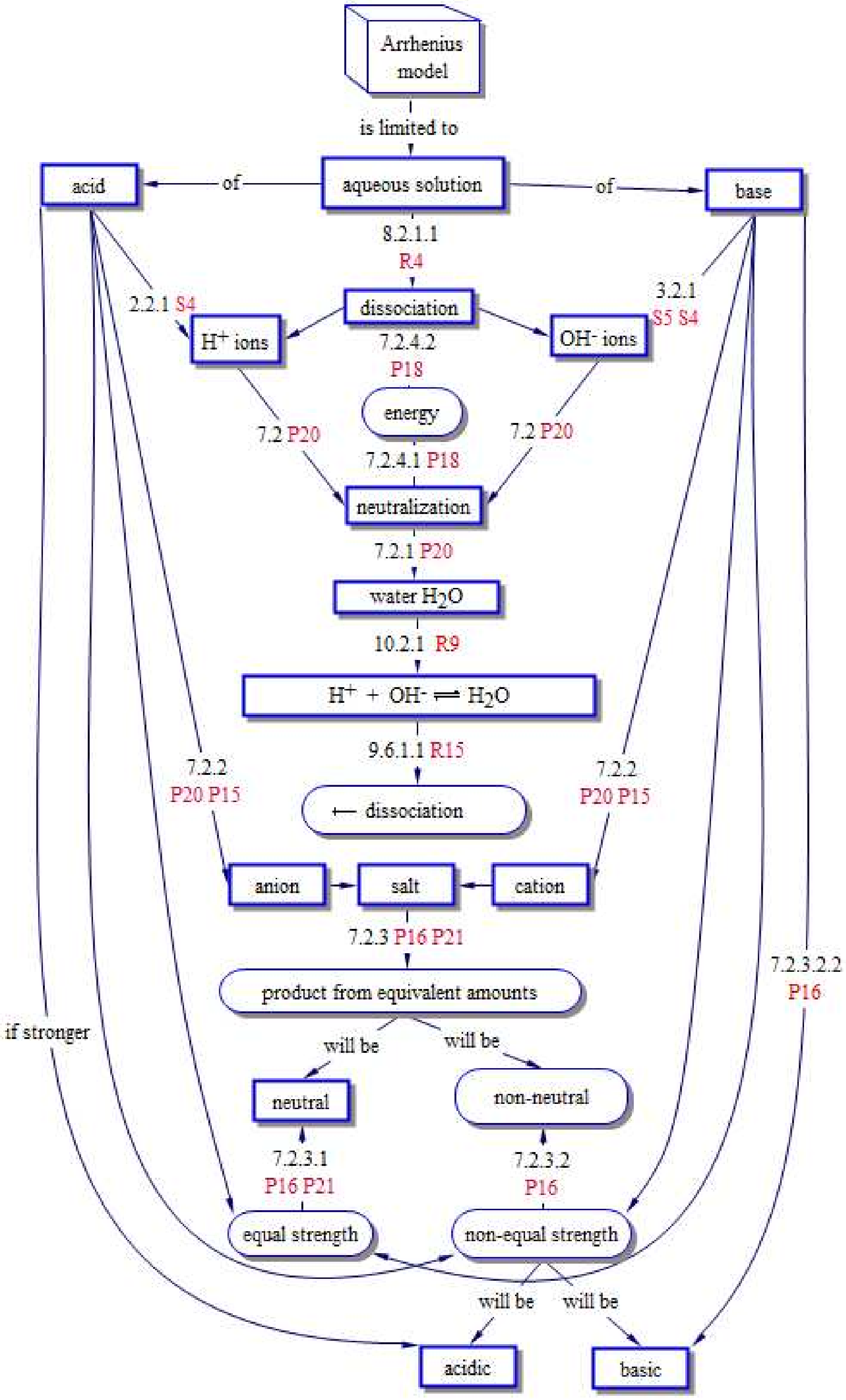

Figure 9.5 Concept map for Arrhenius model of acid-base reactions

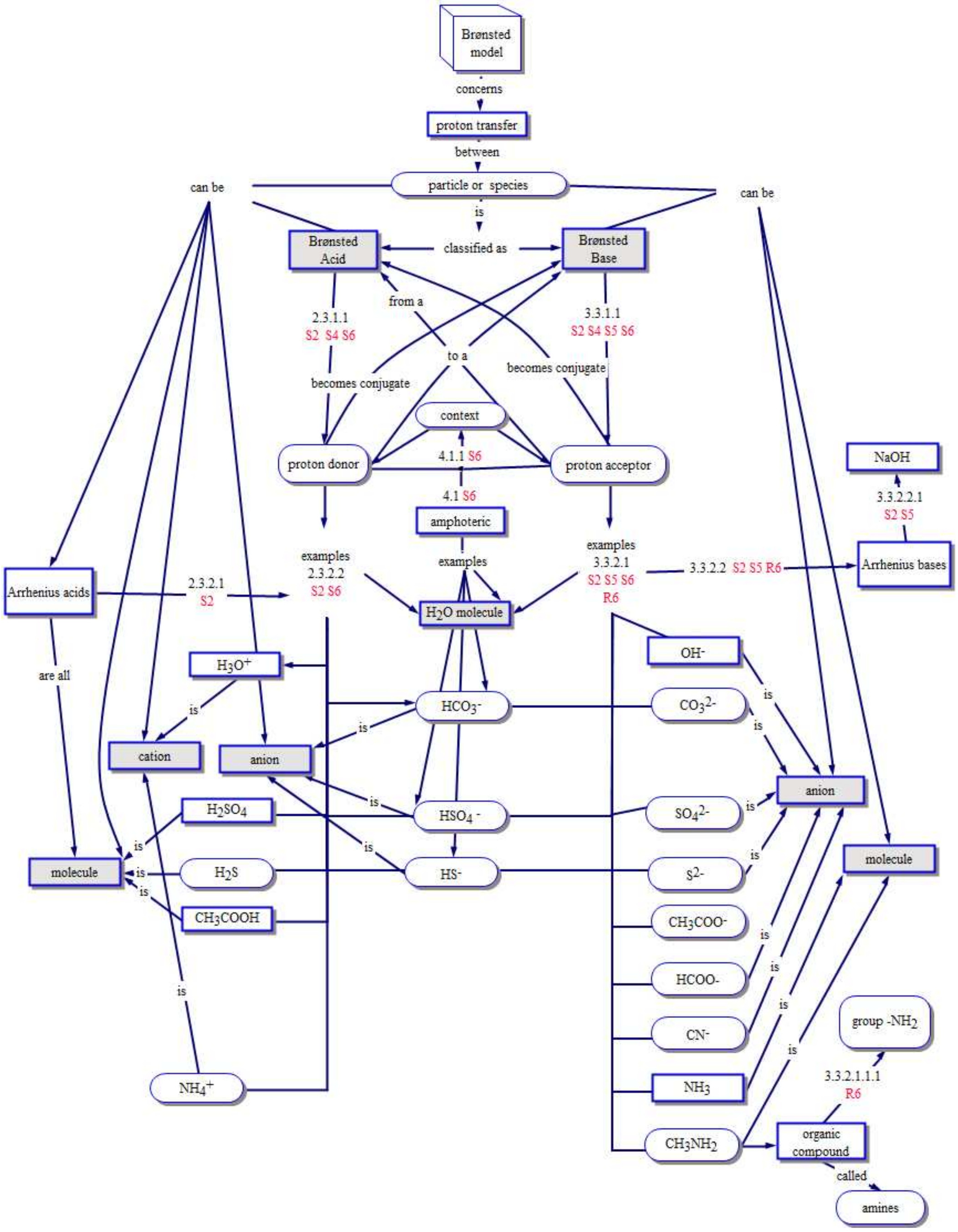

Figure 9.6 Concept map for Brønsted model of acid-base species

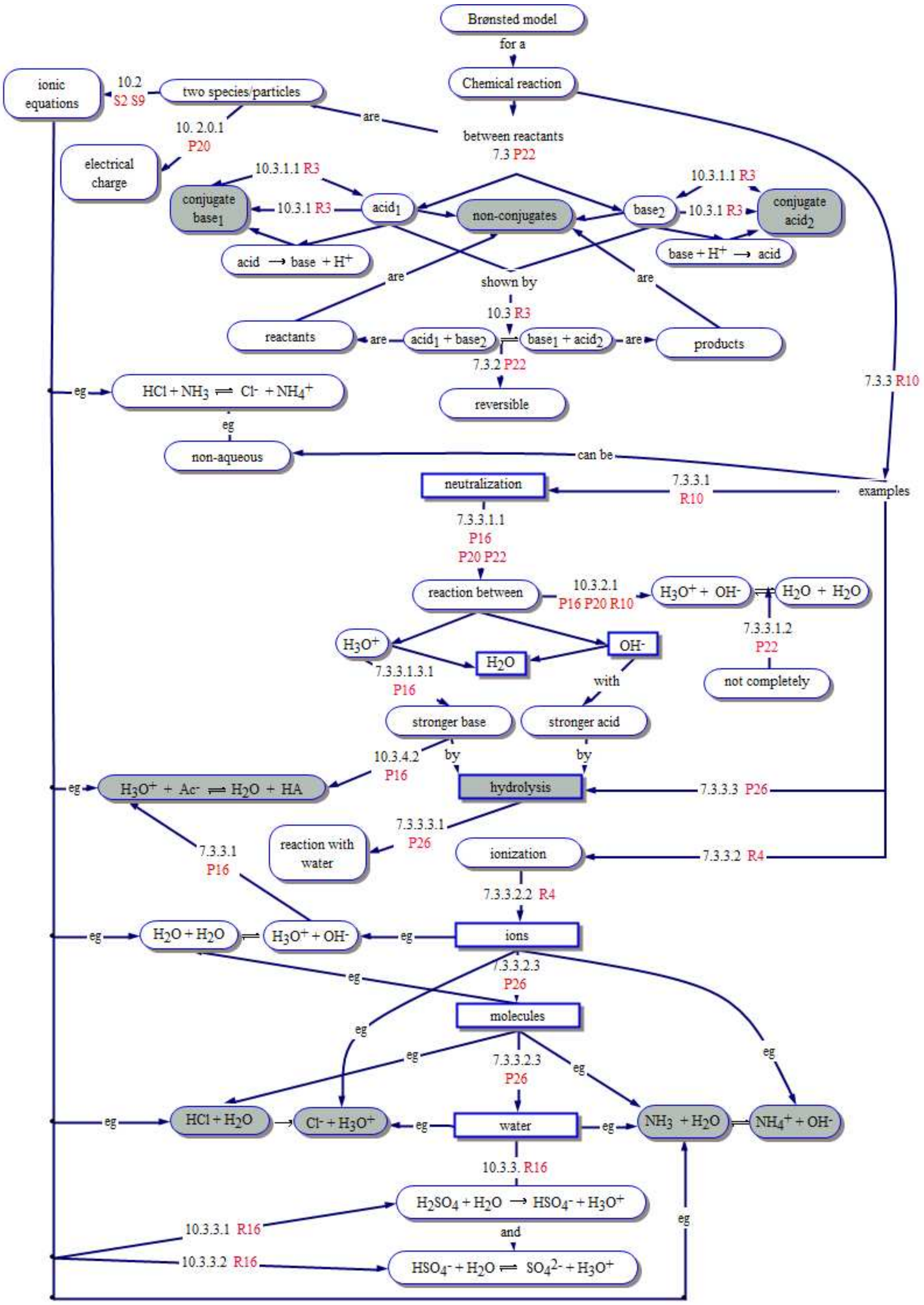

Figure 9.7 Concept map for Brønsted model of acid-base reactions

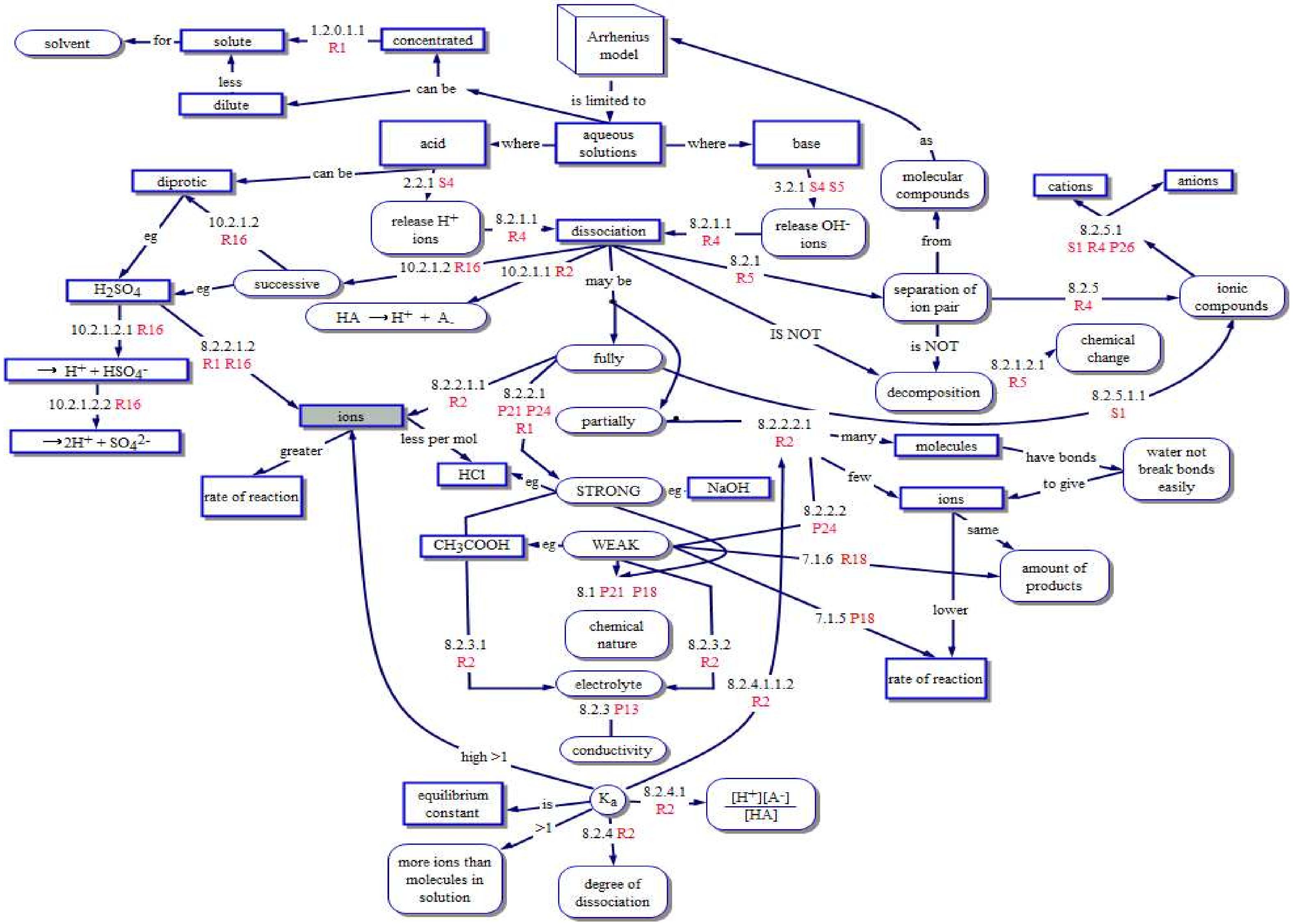

Figure 9.8 Concept map for Arrhenius model of acid-base strength

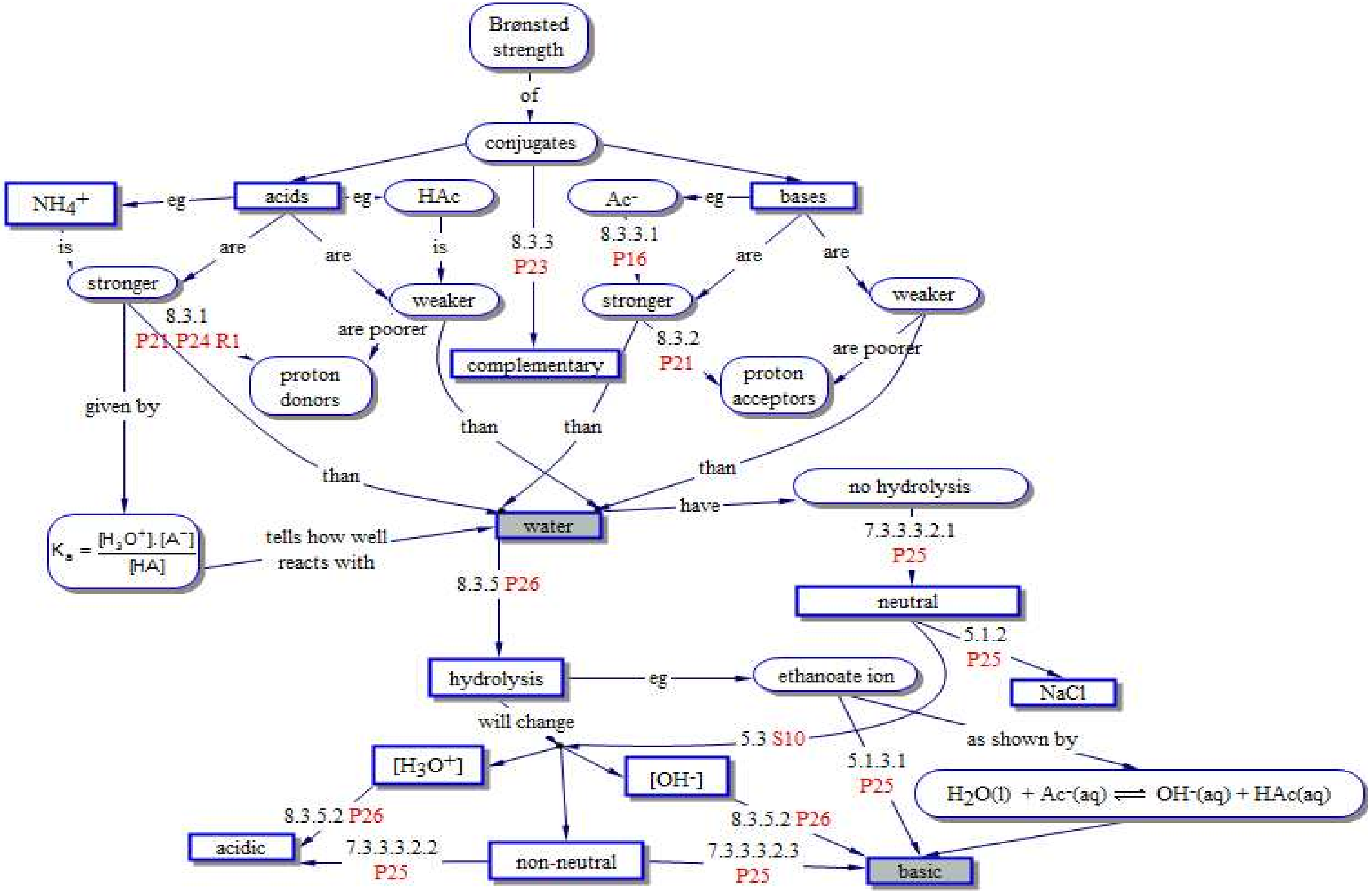

Figure 9.9 Concept map for Brønsted model of acid-base strength

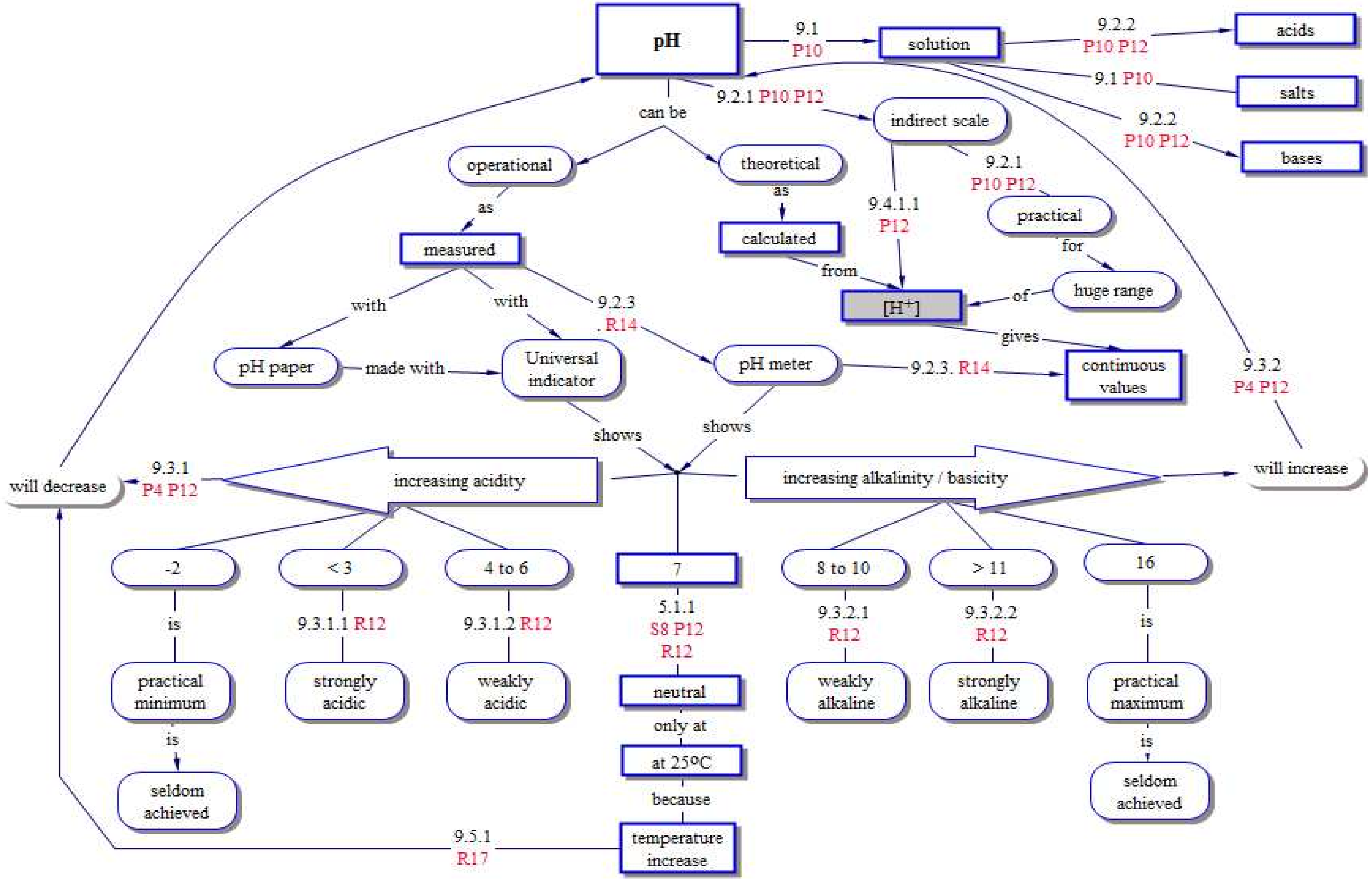

Figure 9.10 Concept map for qualitative aspects of pH

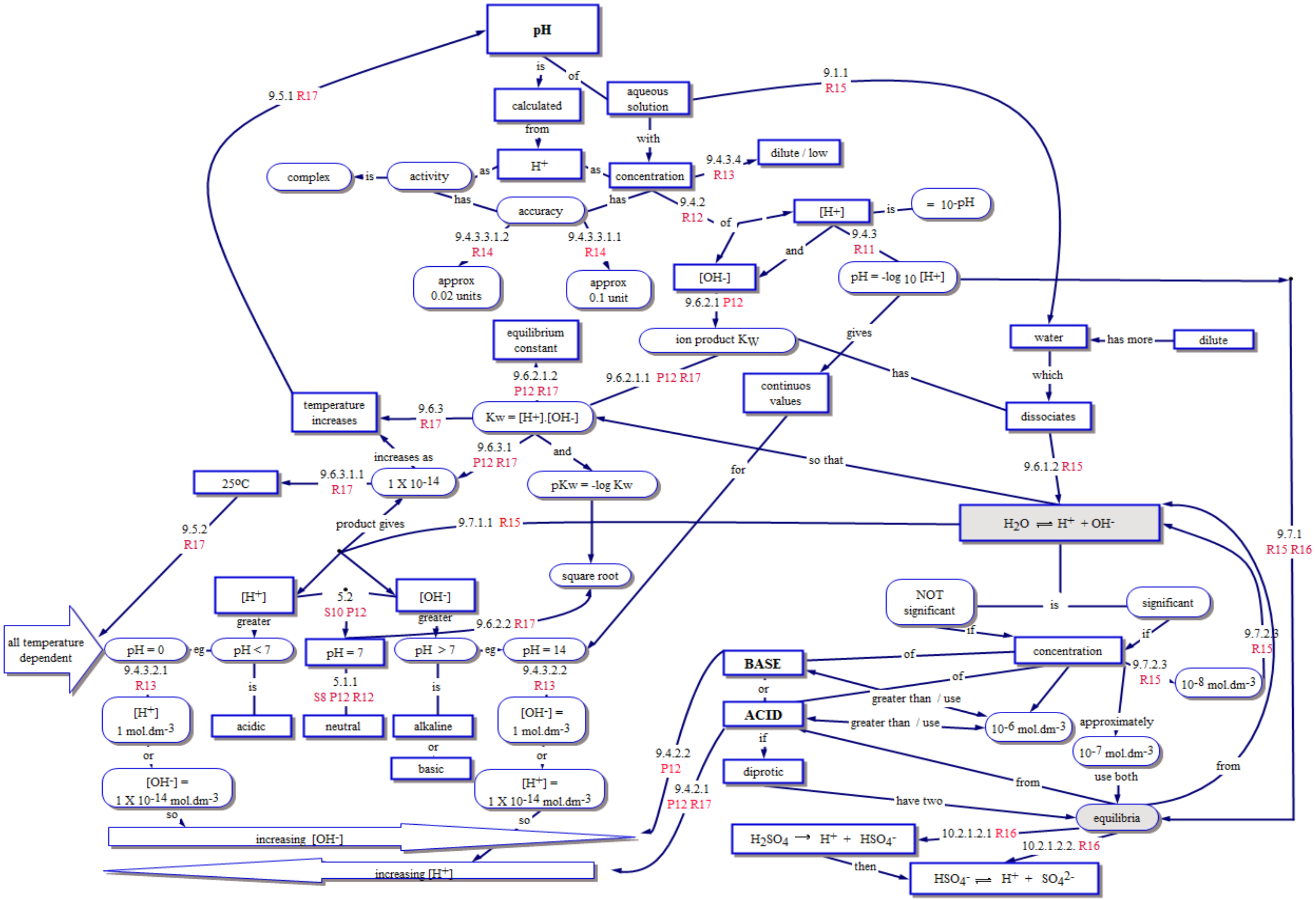

Figure 9.11 Concept map for quantitative aspects of pH

9.2 EVALUATION OF PROPOSITIONAL KNOWLEDGE STATEMENTS

To address research sub-question 5a, the composite list of propositional statements was compared to criteria given in Section 4.6.1 so as to judge whether they reflect a curriculum which is simple enough for school students without compromising the historical models. For the readers' convenience, the criteria and the way in which they would be evaluated were given in a flip-out form as Table 4.5 on page 77. The five criteria involved pragmatism, parsimony, consistency, transparency and consensual acceptance.

9.2.1 Evaluation for pragmatism

The first criterion concerns the appropriateness of the set of propositional knowledge as pragmatic curriculum models. In other words, were they suitable for teaching students? Examining the propositions in Table 9.1 shows that nearly all (90%) were derived in response to at least one student difficulty. It can reasonably be assumed that chemistry education researchers would study conceptions in topics which are within students' cognitive development. In other words they would not expect elementary students to know about proton transfer. Furthermore Section 5.4 shows that many researchers claim to have evaluated the face validity of research probes with suitable experts. Accordingly, I can argue that 88% of propositions were appropriate for students of various ages as covered in the original studies. The remaining propositional statements, not directly derived from student difficulties, were included for three reasons. Firstly, some propositions were added for symmetry of statements concerning both acids and bases (e.g. 7.3.3.1.3.2 complements 7.3.3.1.3.1). In other cases, they were needed to provide links between propositions derived from difficulties (e.g. 8.2.2 was added to link 8.2.2.1 and 8.2.2.2). Thirdly, further propositions were needed for completeness, including aspects of certain concepts besides those that had presented difficulties (e.g. 9.7.2.1. and 9.7.2.2 complement 9.7.2.3). Therefore none of the extra statements were added to embrace topics not already included, nor were they added to show finer detail in a topic. Therefore the remaining 12% (and hence all) of the propositional statements reflect knowledge included and deemed appropriate for various ages in an acid-base curriculum. But does it reflect a complete curriculum? This aspect will be evaluated next.

Comparison of the propositional statements in Table 9.1 with three high school curricula (see Section 4.6.1) this indicated that all the core acid-base topics were included, but that some aspects could be missing. The missing aspects are shown in Table 9.2 and a discussion of these aspects follows.

Table 9.2 Showing typical high school topics not included in Table 9.1

	Topic missing from Table 9.1	Curriculum publication
1	HNO_3 as an example of acids	Nakhleh & Krajcik (1994)
2	Meaning of chemical formulae	Nakhleh & Krajcik (1994)
3	Calculations of concentration	Nakhleh & Krajcik (1994)
4	The cause of acid rain and acid soil	Ross & Munby (1991)
5	Hydrochloric acid in human stomachs	Ross & Munby (1991)
6	Calculations involving acid dissociation constants	Nakhleh & Krajcik (1994)
7	Indicator colour change explained by Le Chatelier's principle	Independent Examination Board (1997).
8	pH graphs in acid-base titrations	Nakhleh & Krajcik (1994)
9	Metal and non-metal oxides as sources of bases and acids	Ross & Munby (1991)
10	Definition of polyprotic acids	Nakhleh & Krajcik (1994)

The first topic in Table 9.2 nitric acid (HNO_3) was deliberately omitted from the list of propositional knowledge for the following pedagogical reasons. Even when dilute, HNO_3 is involved with both acid-base and redox reactions and research shows that students can confuse these two types of reactions (Schmidt & Volke, 2003). Consequently I chose to limit examples of acids to those behaving typically as acids rather than oxidising agents. Topics 2 to 5 were excluded due to the scope of the current project (see Section 4.4.1.) In this regard, Topics 2 and 3 involve underlying chemical principles, beyond acid-base, and Topics 4 and 5 concerned environmental and physiological aspects. Topics 6 to 8 were omitted due to the lack of suitable research into difficulties with the topics. The initial search of publications (see Section 5.3) revealed no research concerning Topics 6 or 7. This is not to say that students do not experience difficulties with this aspects, but rather that these topics have not yet been targeted in studies on student difficulties. The search revealed some research concerning difficulties with graphs of pH in acid-base titrations (Topic 8) but the published data (Nakhleh & Krajcik, 1993; Sheppard, 2006) did not meet the criteria for data used in this study (see Section 4.4.1). Finally, propositions concerning Topics 9 and 10 (metal and non-metal oxides and polyprotic acids) were subsequently incorporated when drawing the relevant concept maps (see Figures 9.2 and 9.4). This analysis shows that the propositional statements in Table 9.1 encompass all essential aspects of a typical high school curriculum. There are some peripheral topics omitted. In this way they are pragmatic, as they include statements simple enough for school students.

9.2.2 Evaluation for parsimony

Parsimony infers that propositions will include only that which is necessary for understanding the topic while avoiding superfluous information. The propositions concerning definitions and examples had grown incrementally as more difficulties were described; perhaps some of this detail was unnecessary. Furthermore the whole set of propositions was extensive and perhaps some information was duplicated. These aspects are examined for parsimony.

9.2.2.1 Examination of Brønsted definitions

The Brønsted definitions given below have become more complex, and possibly too wordy, during the course of the analysis.

- Molecules or ions are classified as Brønsted acids when they donate a proton (hydrogen ion) to a base (2.3.1.1)
- Molecules or ions are classified as Brønsted bases when they accept a proton (hydrogen ion) from an acid (3.3.1.1.)

Definitions need to show the aspects of a concept that are both individually necessary and jointly sufficient to label an instance as being an example or non-example of the concept. These aspects have been termed by Herron (1996) as critical attributes. In the case of Brønsted acids or bases, there are three critical aspects:

(i) The acids and bases are species rather than substances;
(ii) The classification is not absolute but according to behaviour in the context of a particular reaction; and finally,
(iii) For the reaction to take place there must be present both an acid to donate protons and base to receive them.

The definitions given above include all critical aspects but give nothing more than the critical aspects. Moreover all these aspects present difficulties for students (S2, S4, S5, S6 and R6). By contrast, the oft quoted “acids are proton donors, bases are proton acceptors” (e.g. Schmidt, 1995; Brady & Holum, 1993) is little more than an algorithm or mnemonic; that is, ‘ritual knowledge’ (Perkins, 1999). It certainly does not show students the critical aspects of the Brønsted conception of acids and bases. In this case, simplifying does not clarify. The detail is necessary.

9.2.2.2 Evaluation of the acid-base examples

Next the sets of acid-base examples and non-examples given in the propositions were examined. In particular proposition number 3.3.2.1 gives 14 examples of Brønsted bases, which were all included in response to identified difficulties, but the overall number might be excessive.

Consequently, the acid or base examples implicated in student difficulties (5 Arrhenius acids, 5 other Brønsted acids, 4 Arrhenius bases and 11 Brønsted bases) could be trimmed down to a set of teaching examples as shown in Table 9.3 below. The table also gives the reason for inclusion of each example.

Table 9.3 Examples of acids and bases with reasons for their inclusion

Acid Examples	**Reason**	**Base Examples**	**Reason**
HCl	Prototypic Arrhenius and Brønsted acid, molecule, monoprotic	NaOH or KOH	Prototypic Arrhenius base, not Brønsted base
HCOOH or CH_3COOH	Carboxylic acid (Arrhenius and Brønsted), not a base despite the OH group	$Al(OH)_3$ or $Zn(OH)_2$	Amphoteric Arrhenius bases
H_2SO_4 or H_3PO_4	Polyprotic Arrhenius and Brønsted acid, can be represented with OH group, conjugate base is amphoteric	S^{2-}, CO_3^{2-} or SO_4^{2-}	Brønsted base, anion, conjugate acid is amphoteric
H_3O^+	Brønsted acid involved in aqueous neutralization reactions	OH^-	Prototypic Brønsted base, not Arrhenius base, anion
H_2O	Brønsted acid, molecule, not Arrhenius acid, amphoteric, gives specific difficulties	H_2O	Brønsted Base, not Arrhenius base, amphoteric, molecule, gives specific difficulties
HS^- , HCO_3^- or HSO_4^-	Brønsted acid, anion, amphoteric	HS^-, HCO_3^- or HSO_4^-	Brønsted base, anion, amphoteric
		‘NH_4OH’	Postulated as Arrhenius base, not needed in Brønsted model
NH_4^+	Brønsted acid, cation	NH_3	Prototypic Brønsted base, not Arrhenius base, molecule

The table shows that a minimum of 15 examples and non-examples are needed to address specific difficulties identified in the previous three chapters. However, Brønsted acids and bases should be taught along with their conjugates (see Difficulty R3, Section 8.2.2.1) which would add to the list. For a curriculum, a practitioner may select from these examples those which are suitable for the students, and which illustrate the necessary range of variable attributes (Herron, 1996) as shown in the table. In the Brønsted model variable aspects include: acid or base species may be molecules (e.g. HCl) or anions (e.g. HS^-), acids may also be cations (e.g. NH_4^+) and bases may or may not have OH groups (e.g. OH^- and S^{2-}). Furthermore, non-examples are important in order to show the limitation of a concept. Therefore, H_2O is given as a non-example of both Arrhenius acids and bases, while NaOH is given as a non-example of a Brønsted base to reflect the distinction between models. The hypothetical ‘NH_4OH’ is introduced to show how the Arrhenius model accommodated the basic properties of ammonia in a protective belt while the Brønsted model accommodates NH_3 at its core. Other sets of examples were similarly examined, and Table 9.1 shows propositions giving the final lists of examples which are necessary to illustrate aspects of a concept.

9.2.2.3 Evaluation of the set of propositions

Having verified the propositions contained no superfluous detail, the concept maps (Figures 9.1 to 9.11) were used to identify propositions which duplicated conceptual links. For example the propositional statement “Neutral solutions have a pH of 7” was used in the context of understanding neutrality (S8) with code 5.1.1, but also in the context of the pH scale (difficulties P12, R11, R12 and R17) with the code 9.4.1. As the two statements were on different pages of the list of propositional statements, the duplication was not immediately obvious until I attempted to allocate codes on the concept map. The two were then reconciled into a single statement (5.1.1) mapping to all the difficulties. Two other duplications were treated similarly. Through re-examination of propositions concerning definitions and examples as well as the whole set of propositional statements on concept maps, superfluous information has been eliminated to meet the criterion of parsimony.

9.2.3 Evaluation for consistency

Consistency implies coherency within each model, with no hybrid models (see Section 2.1.3) which might compromise its hard core. In this way the integrity of each model was to be ensured. When the propositional statements were integrated as links on concept maps, each map except Figure 9.1 reflected a single model, in that it was limited to representations and examples particular to the model concerned. For instance, the Arrhenius acid-base strength concept map (Figure 9.8) incorporates dissociation, whereas this term does not appear on maps concerning the Brønsted model, where it would be inappropriate. Furthermore, each propositional statement was allocated to a particular model in Table 9.1 and this table also shows that each statement could be allocated to at least one map. Inconsistencies between these two ways of representing propositions were used to identify anomalies and subsequently resolve them. One such potential inconsistency arose in the propositional statements concerning hydrolysis of salts, derived in response to Difficulty P25 (see Section 7.5.2.1). To elaborate, the propositional statements in Table 9.1 were initially placed under the Brønsted model because it provides a direct explanation for non-neutral salt solutions which is simpler than that according to the Arrhenius model (see Sections 3.3.2.2 and 3.3.3.5). However, at that stage, I had phrased the statements according to the Arrhenius model, as they involved predicting the acid/base nature of a solution of salts. When I attempted to incorporate the propositions into Figure 9.9 (Brønsted model for acid-base strength) the inconsistency became apparent. So revisions were made as shown in Table 9.4 which follows.

Table 9.4 Revision of propositional statements to fit the Brønsted model

Code	Original Statement	Revised Statement – Brønsted model
5.1.3	Salts may have neutral or non-neutral solutions (7.3.3.3.2)	Re-coded to salts (5.1.3)
5.1.2	NaCl forms a neutral aqueous solution (7.3.3.3.2.3)	Eliminated, duplicates 5.1.2 NaCl forms a neutral aqueous solution
5.1.3.1	Sodium ethanoate has a basic solution (7.3.3.3.2.3.1)	Re-coded to salts (5.1.3.1)
7.3.3.3.2.1	Salts from strong acids and strong bases will have neutral aqueous solutions.	Revised: Salts where ions are weaker Brønsted acids or bases than water will have neutral solutions
7.3.3.3.2.2	Salts from strong acids and weak bases will have acidic aqueous solutions	Revised: Salts where ions are stronger Brønsted acids than water will have acidic solutions
7.3.3.3.2.3	Salts from weak acids and strong bases will have basic aqueous solutions.	Revised: Salts where ions are stronger Brønsted bases than water will have basic solutions

The first three propositions in the table were re-coded so they now fall under macroscopic properties of salts in Table 9.1. Duplication concerning NaCl was then obvious so that statement was eliminated in the interests of parsimony (see Section 9.2.2). When trying to incorporate the original statements onto any of the concept maps for the Brønsted model, it was clear there were no appropriate links, because the Brønsted model does not focus on particular substances (acid and base) which tended to be neutralized to give the salts, as in the last three original propositions 7.3.3.2.1 etc above. As a result, the propositions were then rephrased as shown in the last column of the table. The subtle but important difference between the species that is considered weak or strong according to the two models is especially evident in statement 7.3.3.3.2.1. To amplify, in the Arrhenius model, the original acid or base from which the salt was produced is strong whereas Brønsted acids and bases are the ions of which the salt is now composed. This illustrates how important it is to see the propositional statements in relation to each other as on a concept map. Once all the propositions could be incorporated appropriately into at least one concept map for the relevant model, coherence within each model was achieved and hybrid models were avoided. Accordingly, the criterion of consistency can be met.

9.2.4 Evaluation for transparency

To have transparency, it was necessary that the propositional statements make the hard core of each mode clear, that is define its context and limitations. The context of the operational model is shown by the acid-base definitions and the products of neutralization reactions being a salt and water (propositions 1.1.1; 1.2; 3.1; 7.1.2.1; 7.1.2.2), as well as its household applications and use in titrations. Furthermore the appropriate equations with formulae for substances are emphasised (10.1; 10.1.1). With no mention of ions or molecules in the propositional statements, the macroscopic limitation is evident. The aqueous context of the Arrhenius model is given in the acid and base definitions as well as the product of neutralization reactions (2.2.1; 3.2.1, 10.2.1; 10.2.1.1) and its particular representation of neutralization reactions (10.2.1). For the Brønsted model, there are propositions showing its wider application beyond neutralization reactions (7.3.3.2 and 7.3.3.3) and further statements (not implicated in difficulties) were added to show its relevance beyond aqueous solutions (7.3.1 and 7.3.1.1). In addition there are numerous equations in the characteristic ionic format (10.3). Moreover, the comprehensive list of examples and non-examples already given in Table 9.3 (see Section 9.2.2) shows the different limits of the two theoretical models. By these means, the hard core of each model was made transparent.

9.2.5 Evaluation for acceptability by consensus

Finally it is necessary to verify the acceptability of the propositions in Table 9.1 to experts, in this case, chemists. The analysis of difficulties in Chapters 6, 7 and 8 showed that propositional statements were constantly compared to publications by experts in chemistry and chemistry education. For instance see S7 concerning the relevance of acids and bases (Section 6.4.1) and R14 concerning pH of very dilute solutions (Section 8.4.2.2). This meant that the propositions were constantly checked against expert opinion and anomalies resolved as with P16 (Section 7.4.1.2). Consequently I was confident that the list of propositional statements would find acceptance with two expert chemists at the University of KwaZulu-Natal. They both accepted the list with a few changes which were easily accommodated. However they did not treat the task in a cursory fashion; instead there were 29 comments, indicting the care taken in examining the list. The majority of the comments concerned typographic corrections, some corrected grammar, but eight concerned chemical principles. The latter points were either accepted or resolved through discussion. Changes included removing PH_3 as an example of a base ("maybe not a good example – it is not readily protonated"), putting NH_4OH "into quotation marks to indicate its hypothetical nature". One important change was in the statements concerning Brønsted acid-base strength of conjugates, where together we reworded the propositional statements 8.3.3; 8.3.3.1 and 8.3.5. Accordingly, there was consensus among expert chemists concerning the propositional statements given earlier in this dissertation and as a composite list in Table 9.1.

9.2.6 Summary of evaluation of propositional statements

In short, evaluation of the propositional statements in Table 9.1 against the criteria given in Table 4.3 shows that through the method of mapping student difficulties, it has been possible to derive propositional knowledge statements reflecting pragmatic curriculum models that are pragmatic; in other words simple enough for students' stage of development, while still being acceptable to experts, and maintaining the integrity of the models. The set of propositions indicates the minimum knowledge necessary for understanding an operational model and the Arrhenius and Brønsted theoretical models. There is no intention that this list be given in this format to students. Their meaning lies in the proposition, not in the exact words. Moreover, they are decontextualised, and so need to be developed into learning experiences for students. What is more, they do not reflect a complete school curriculum. Nevertheless they represent propositional knowledge which has been implicated in studies on student conceptual difficulties. As such they bear closer examination.

9.3 IMPLICATIONS FOR TEACHING AND LEARNING

9.3.1 Implications of the propositional knowledge statements

Some of the 218 separate propositional statements given in Table 9.1 are more complex than others. In other words some may involve only one concept while others include more. Furthermore, the depth of research differs for the difficulties listed by code in Table 9.1 in that only some have been established at Level 4, while others have been described at lower levels. Consequently quantitative data on the propositional statements shows only approximate patterns. Nevertheless some trends are evident concerning in the relationship of individual difficulties or categories of difficulties to propositional knowledge (see Table 9.5 below).

Table 9.5 Numbers of propositional statements according to category of difficulties

Propositional statements	Categories of Difficulty	Number
Total	all	218
Without difficulty	Not applicable	23
Problematic	all	195
Mapped from only one difficulty in any category	all	145
Mapped from two or more difficulties in the same category	S or P or R	24
Mapped from two or more difficulties in different categories	total	26
Overlapped categories	S & P	12
Overlapped categories	S & R	5
Overlapped categories	P & R	7
Overlapped all three categories	S & P & R	2

Difficulty Categories: S (species) P(properties & processes) R(representations)

Table 9.5 shows that the majority (89%) of the propositional statements were implicated in difficulties. This stands to reason as they were nearly all derived in response to student difficulties. Those which have not been implicated in student difficulties (only 11%) were added for reasons given in Section 9.2.1, and have no difficulty codes allocated in Table 9.1.

However, this does not infer that these additional conceptual links are problem-free, because it is possible that they have simply not yet been targeted during research into student conceptions, as was the case with some of the topics in Table 9.2. Furthermore, the set of propositional knowledge in Table 9.1 does represent a large part of a typical high school curriculum (see Section 9.2.1). Accordingly, the high percentage of problematic propositions (those implicated in conceptual difficulties) does reveal that nearly every aspect of acid-base chemistry has been shown to present difficulties for students at some stage in their academic career.

From the table above it can also be seen that most of the problematic propositions (74%) were mapped directly from only one difficulty. This shows a highly specific mapping between propositions and difficulties. This suggest that in most cases, a particular problematic link (be it missing or inappropriate) in a student conception may lead to a specific difficulty, although there might be several potential sources of each difficulty. Initially I anticipated a many-to-many mapping (see Section 4.5.3), instead the results shows that in most cases there is a many-to-one mapping between propositions and difficulties, as illustrated in Figure 9.12 below.

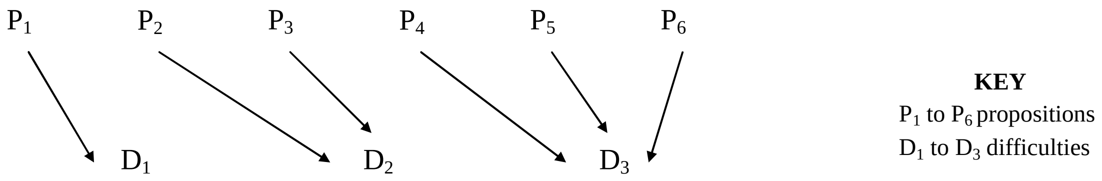

Figure 9.12 Showing the many-to-one mapping between propositions and difficulties

Figure 9.12 shows that proposition P_1 has been implicated in difficulty D_1. The difficulty might be avoided or corrected if appropriate instruction focuses on developing the conceptual link P_1. The diagram then shows that if a student has an inappropriate or missing conceptual link indicated by any one of propositions P_2 or P_3, the student is likely to exhibit only difficulty D_1, whereas problems with propositional links P_4 to P_6 could give rise to difficulty D_3. However the diagram also shows that if a student shows difficulty D_2 or D_3 there might be, respectively, two or three possible problematic conceptual links causing the difficulty. Consequently to find the source of a difficulty in a particular student, several potentially problematic links need to be investigated. This could be achieved through appropriate distractors for diagnostic multiple choice items which each target only one of the propositions and so alert practitioners to the specific link causing the difficulty for a particular student. Finding even one such link to be problematic will indicate the presence of the difficulty.

Looking more globally at the data in Table 9.5 it can also be seen that 87% of the problematic propositions mapped from only one category of difficulty; that is difficulties concerning one of acid-base species (S), properties and processes (P) or representations (R). A very small number of propositions mapped to difficulties overlapping two or more categories. In this regard, the most common overlap was between categories S and P (as for instance propositional statement 2.1.1.3 which mapped to difficulties S1 and P5). Only two propositions mapped to difficulties overlapping all three categories. These were proposition 5.1.1 indicating that neutral solutions have a pH of 7 and proposition 8.2.5.1 describing dissociation into anions & cations. The small percentage of overlap strengthens the appropriateness of the initial category choices for difficulties, which were originally based on the notion that the acid-base reaction concerned more abstract ideas than the acid-base species (Wilson, 1998), and so would lead to a different type of difficulties. Although, I had anticipated that representational difficulties would pervade the whole of the acid-base topic (see Section 2.5.2), the data in Table 9.1 shows this is not so. It appears from Table 9.5 that propositional knowledge relevant to representational difficulties is almost separate to the other propositional knowledge. This means that students need to access an almost separate knowledge base in order to understand the way in which acid-base species and reactions are represented. Consequently, to assist students represent the reaction, practitioners should concentrate on developing the specific links implicated in representational difficulties. In other words, it is not so much the content structure determining the type of difficulty as the type of knowledge required within that structure.

In short, this section indicates that problematic conceptual links indicate specific difficulties or categories of difficulties. The categories of difficulties implicate different aspects of conceptual knowledge which are more related to cognitive development than to conceptual structure of the topic. This idea is then developed further in the next section which shows the interrelations between student difficulties and the content structure (as shown on concept maps).

9.3.2 Implications of the concept maps for acid-base models

The concept maps (Figures 9.1 to 9.11) were constructed in order to evaluate the propositional statements according to the criterion of consistency, (see Section 9.2.3), and they were also useful in ensuring parsimony (see Section 9.2.2). In this section, the relationships within the concept maps are analysed in order to show their implications for teaching acids and bases. A multi-map format was adopted for the concept maps (see Section 9.2.3) but this contrasts with a linear or strictly hierarchical conceptual structure of a topic as supported by Herron (1996). However, this format is in accordance with a curriculum incorporating multiple models which suggests an overlap of concepts (Taber, 2006) or a rhizomorphic curriculum structure, whereby the same concept has several roots, or points of entry (Land *et al*., 2006). In the case of these concept maps, the multiple points of entry represent cross-links, which are common across concept maps (see Section 9.4.1.2). The concept maps in Figures 9.1 to 9.11 are my personal representations of conceptual links in acid-base chemistry, and I do not suggest they are the only way this knowledge could be represented. Accordingly, the analysis which follows, in terms of critical nodes and cross-links has limitations but nevertheless it shows some noteworthy consequences.

9.3.2.1 Analysis of critical nodes on concept maps

The importance of certain concepts and hence the concept map on which they appear can be shown through analysis of critical nodes. These are nodes representing concepts with at least three *incoming* conceptual links and as such they should indicate the depth or richness which is "essential to an appropriate, scientific understanding of acid-base chemistry" (Nakhleh & Krajcik, 1994, p 1084). Table 9.6 below summarises the critical nodes found on the relevant concept maps, together with the difficulties associated with propositions leading *into* the nodes on that map. On the concept maps the critical nodes are shown with shaded backgrounds so that the reader may find them easily. The simplest of the concept maps (Figure 9.1) shows the relationships between acid-base models. It involves the least number of concepts and has no critical nodes. On this map links to the Lewis acid-base model were introduced because, even though the Lewis model is not included in the current project, it will be encountered later by tertiary students. Accordingly, the concept map makes provision for such future links.

The concept maps representing the Operational model show this model requires considerable integration of conceptual knowledge. Figure 9.2 represents one of the most integrated maps, as shown by eight concepts at critical nodes. These are *acidic* [substance] (5 incoming links), *pH* (4 incoming links), and *basic* [substance], *characteristic properties, indicator colour, taste, fruit* and *corrosive* – on both left and right of the map – (each with 3 incoming links). From Figure 9.3 it can be seen that further important concepts for integrating the operational model include *reaction complete* and *gas.* The concepts mentioned reflect the core of an operational model which classifies substances as acidic or basic in terms of macroscopic properties such as pH, indicator colours or, historically, through physical properties such as taste, as found in fruits, and reflects their caustic effect in common names. The model treats reactions, which sometimes produce gases, as proceeding to completion. These are concepts at critical nodes. Accordingly, they are concepts whereby knowledge should be richly integrated. However, from Table 9.6 it can be seen that every one of these concepts has been implicated in more than one student difficulty; in particular pH and indicator colour are each associated with four difficulties. Consequently students are likely to have inappropriate or compromised conceptions of these essential formative aspects. The operational model as the relationship between species and their properties is not trivial, despite usually being taught early in students' careers. Accordingly teachers need to be aware that students are unlikely to understand more advanced concepts if these problems are not first addressed.

Table 9.6 Critical nodes identified in concept maps

Figure number	**Central topic of map**	**Concept at critical node**	**Number of incoming links**	**Difficulties associated with links into the node on that figure**
9.2	Operational model species	acidic	6	S1
		basic	4	S4
		characteristic properties	3	S1 P4
		pH	4	S1 P8 P12 P20
		indicator colour	3	S1 P5 P8 P9
		taste	3	S1 P5
		fruit	3	S7
		corrosive (LHS & RHS)	3 + 3	P1 & P4
9.3	Operational model reaction	reaction complete	3	P16 P18 P22
		gas	3	P11 P19
9.4	Arrhenius model species	OH group	3	S2 R7
9.6	Brønsted model species	Brønsted acid	3	None identified
		Brønsted base	3	None identified
		anion (LHS & RHS)	4 + 7	None identified
		cation (LHS)	3	None identified
		molecule (LHS & RHS)	5 + 3	None identified
		H_2O molecule	3	S2 S5 S6 R6
9.7	Brønsted model reaction	conjugate base	3	R3
		conjugate acid	3	R3
		non-conjugates	4	None identified
		hydrolysis	3	P26
		$H_3O^+ + Ac^- \rightleftharpoons H_2O + HAc$	3	P16
		$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$	4	None identified
		$HCl + H_2O \rightleftharpoons Cl^- + H_3O^+$	4	None identified
9.8	Arrhenius model Strength	ions	4	R1 R2 R16
9.9	Brønsted model Strength	water	5	None identified
		basic	4	P25 P26
9.10	pH qualitative concepts	$[H^+]$	3	P12
9.11	pH quantitative concepts	$H_2O \rightleftharpoons H^+ + OH^-$	3	R15
		equilibria	3	R15 R16

The concept maps for the Brønsted model include those with second highest number of concepts at critical nodes. In this model acid-base reactions (Figure 9.7) has seven which indicate that propositional knowledge concerning Brønsted acid-base reactions are integrated through key concepts of *acid-base conjugate pairs* and *non-conjugates, hydrolysis* with two classic examples of *ionization*. Unlike the case of Figure 9.2, there are only three difficulties associated with this whole group of concepts. I suggest this disparity is more likely to be due to research not having targeted these concepts rather than these concepts being without difficulty. Further concepts appearing as critical nodes on other concept maps for the Brønsted model include six on Figure 9.6: *Brønsted acid, Brønsted base*, *molecule and anion (both concepts on left and right)*, *cation* (all showing no identified difficulties) and H_2O *molecule* (4 associated difficulties) and two on Figure 9.9: *water* and *basic* (2 associated difficulties). Practitioners would do well to centre instruction of the Brønsted model on these concepts, rather than neutralization which is not at a critical node, as it is not a key concept in the model.

When studying the concept maps concerning the Arrhenius model (Figures 9.4, 9.5 and 9.8) further critical nodes appear in both Figures 9.4 and 9.8, with none on Figure 9.5. From those with critical nodes, it can be seen that *OH group* (Figure 9.4) and *ions* (Figure 9.8) are central concepts in the Arrhenius model. Propositional knowledge concerning pH may also be integrated through the concepts at critical nodes of H^+ (Figure 9.10) and *equilibria* and $H_2O \rightleftharpoons H^+ + OH^-$ (Figure 9.11). All four of these concepts are assocatied with difficulties.

This analysis of concept maps has confirmed earlier claims concerning two of the concepts at critical nodes, namely *gas* or, by inference, bubbles (Nakhleh & Krajcik, 1994) on Figure 9.3 and *ions* (Nakhleh & Krajcik, 1994; Johnstone, 2002) on Figure 9.8. In summary, using concept maps to show two aspects, namely the relationships within the acid-base topic and the difficulties associated with conceptual relationships, has two immediate benefits. In the first place, it identifies concepts which are important for having richly integrated understanding of the topic and it also shows where student difficulties are associated with these concepts. The latter will obstruct achieving the first. This greater insight can be used to design appropriate teaching interventions, according to the category of the difficulties.

9.3.2.2 Analysis of cross-links between concept maps

As with critical nodes, cross-links are also points where knowledge can be conceptually integrated. They differ from critical nodes (which integrate propositions around one concept) in that they integrate concepts across topics. They could link different sections of one concept map (e.g. "*eyes & skin*" on Figure 9.2) or they may involve concepts which appear on more than one map (e.g. "neutral" on Figures 9.2, 9.3 and 9.9 to 9.11). Where these links exist in student conceptions, they are "important indicators of understanding" (Nakhleh & Krajcik, 1994, p 1083). When constructing the concept maps, I initially chose the concepts *acid*, *base* and *pH* to be the cross-links which appear on several concept maps. However many more cross-links arose for concepts as all the propositions were incorporated. Such cross-linked concepts have been shown on the relevant concept maps as rectangular shapes (rather than the normal oval). The proportion of concepts on each map which are cross-linked, in that they appear on two or more concept maps, are summarised below (see Table 9.7). Furthermore, information from Table 9.1 has been extracted to indicate which propositions may be found on more than one concept map (also see Table 9.7 below).

Table 9.7 Prevalence of cross-linked concepts and propositions

		Figure number for concept map										
		9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	9.10	9.11
Propositional statement code	**Percentage of concepts cross-linked**	61	36	41	41	73	53	18	51	48	29	52
	Propositional statement											
1.1.1	Operational definitions indicate how a physical quantity might be recognised or measured.	x	x	-	-	-	-	-	-	-	-	-
1.2.0.1	Properties in concentrated solutions may differ from those in dilute solutions	-	x	-	-	-	-	-	x	-	-	-
2.2.1	Arrhenius acids are substances that release hydrogen ions in aqueous solution.	x	-	-	x	x	-	-	x	-	-	-
2.3.2.1	Brønsted acids: examples include all Arrhenius acids	-	-	-	x	-	x	-	-	-	-	-
3.2.1	Arrhenius bases are substances that release hydroxide ions in aqueous solution.	-	-	-	x	x	-	-	x	-	-	-
3.3.2.2	Brønsted bases: examples do not include Arrhenius bases	-	-	-	x	-	x	-	-	-	-	-
4.1	Amphoteric species are those that can behave both as an acid and a base	-	x		x	-	x	-	-	-	-	-
5.1.1	Neutral solutions have a pH of 7.	-	x	-	-	-	-	-	-	-	x	x
5.1.2	NaCl forms a neutral aqueous solution .	-	x	x	-	-	-	-	-	x	-	-
5.1.3.1	Sodium ethanoate has a basic solution	-	-	x	-	-	-	-	-	x	-	-
8.2.1.1	Arrhenius acids and bases dissociate into ions in aqueous solution.	-	-	-	-	x	-	-	x	-	-	-
9.5.1	pH will decrease with increasing temperature.	-	-	-	-	-	-	-	-	-	x	x
10.2.1	Arrhenius model: neutralization reactions may be represented as: $H^+ + OH^- \rightleftharpoons H_2O$	-	-	-	-	x	-	-	-	x	-	-
10.2.1.2.1	$H_2SO_4 \longrightarrow HSO_4^- + H^+$	-	-	-	-	-	-	-	x	-	-	x
10.2.1.2.2	$HSO_4^- \rightleftharpoons SO_4^{2-} + H^+$	-	-	-	-	-	-	-	x	-	-	x

As defined earlier, topics which help the most to integrate knowledge or require the most integrated knowledge are indicated by a high proportion of cross-linked concepts as well as propositions which appear on many different maps. Looking down the columns of Table 9.7 shows that some topics have fewer cross links than others. For example, with only two propositions cross-linked, an overview of acid-base models (Figure 9.1) will not necessarily inhibit learning specific acid-base models. Instead, learning different acid-base models provides multiple points of entry (as shown by the 61% of concepts that are cross-linked) into the historical modes and notions about the nature of science (as in a rhizomorphic curriculum).

The Arrhenius model, by contrast, shows intensive linking to other acid-base topics. To amplify, acid-base species (Figure 9.4) and Arrhenius acid-base strength (Figure 9.8) each have five cross-linked propositions, while the map for Arrhenius acid-base reactions (Figure 9.5) has the most cross-linked propositions of all the maps. Furthermore Figure 9.5 has an anomalously high (73%) proportion of cross-lined concepts. This suggests that the Arrhenius model provides important opportunities for integrating chemical knowledge concerning acid-base concepts. This contrasts with the view of Hawkes (1992) who advocates not teaching the Arrhenius model in order to avoid confusion between models. This problem might be off-set if care is taken to show the different contexts, strengths and limitations of each model.

In a school context the Brønsted model stands almost alone, as there are few cross-links to other models. In particular Figure 9.7 depicting Brønsted acid-base reactions has no propositions cross-linked to other maps, and only 18% of the concepts are included on other concept maps. This means for example that students can probably understand pH (Figures 9.10 and 9.11) without understanding how Brønsted acid-base reactions are modelled. However, it also suggests another reason for student difficulties with the Brønsted model (besides the high number of critical concepts discussed above) is its inaccessibility due to very few links to prior knowledge. Table 9.7 indicates that appropriate points of entry could be through propositions which appear as cross-links in other maps.

Propositions that appear on several concept maps (as shown in Table 9.7) indicate points where prior knowledge might be accessed when introducing new topics. For instance the propositional statement for the Arrhenius acid definition (2.2.1) can be found on four different maps, indicating it is a necessary part of understanding acid species, acid-base reactions and acid-base strength in the model, but also showing how this model links to others. Propositions concerning Arrhenius acids (2.2.1.1and 2.3.2.1) and bases (3.2.1 and 3.3.2.2) show how these link to or differ from Brønsted acids and bases. The amphoteric definition (4.1) is a useful link for acid-base species across all three models while ideas concerning neutrality (5.1.1 and 5.1.2) are a good link from operational and Brønsted models to ideas about pH. There are also ten propositions which are each found on two maps.

To sum up, analysis of cross-links between concept maps shows which topics are well integrated with other topics, and which have few points of access to prior knowledge. It also shows which propositions could be useful for providing these links. The fifteen propositions shown as cross-links between maps represent points where knowledge should be conceptually integrated, but as indicated in Table 9.1, every one of these cross-links was implicated in student difficulties. A wider analysis of difficulties shown across the concept maps follows.

9.3.2.3 The distribution of difficulty categories on the concept maps

There are noteworthy patterns in the categories of student difficulties particular to each map. Three categories were used for the difficulties in Chapters 6, 7 and 8, namely those concerning acid-base species (S difficulties), acid-base properties and processes (P difficulties), or representations encountered in acid-base chemistry (R difficulties). For each of the concept maps Table 9.8 (below) summarises the categories of difficulties associated with the propositions. Propositions implicated in two or more categories of difficulties – termed an overlap – are indicated by SR, SPR etc. The numbers in Table 9.8 differ slightly from those in Table 9.5 because some propositions appeared on more than one concept map, as discussed in the previous section.

Table 9.8 Numbers of propositions implicated in each category of difficulty

Figure	**Main topic of concept map**	**Total troublesome propositions**	**Category or Overlapped Categories**							**% with overlap**
			S	**P**	**R**	**SP**	**SR**	**PR**	**SPR**	
9.1	Overall models	7	*7	0	0	0	0	0	0	0
9.2	Operational model acid-base species	36	9	*17	1	8	0	0	1	25
9.3	Operational model reaction	24	0	*19	2	3	0	0	0	13
9.4	Arrhenius model species	20	*10	0	4	2	1	3	0	30
9.5	Arrhenius model reaction	14	2	*9	3	0	0	0	0	0
9.6	Brønsted model species	10	*7	1	0	2	0	0	0	20
9.7	Brønsted model reaction	23	0	10	*12	0	0	1	0	4
9.8	Arrhenius model strength	24	3	5	*14	0	0	1	1	8
9.9	Brønsted model strength	12	1	*9	1	1	0	1	0	15
9.10	pH qualitative	11	0	*5	*5	0	0	1	0	9
9.11	pH quantitative	24	0	1	*18	1	0	3	1	21

Difficulty categories: S – species, P – properties and processes, R – representations,
Overlapped difficulty categories: SP – species and processes, SR – both species and representations,
PR – both processes and representations, SPR –all of species, processes and representations
*shows the most frequently occurring category on the concept map

Figure 9.1 is the only map where all difficulties fell into one category, in this case acid-base species. All the other concept maps involved more than one category of difficulty. However, for some there was still one dominant category of difficulty. For instance when learning about the Brønsted model for acid-base species (Figure 9.6), students experience mostly species (S) difficulties and Chapter 6 indicated that such difficulties were primarily due to students not accommodating definitions according to different models. Similarly, most difficulties encountered with the operational model of acid-base reactions (Figure 9.3) or the Brønsted model for acid-base strength (Figure 9.9) are with acid-base processes (P) while difficulties with quantitative aspects of pH (Figure 9.11) are most frequently with representations (R). Accordingly, teaching strategies which target these aspects may address many of the difficulties encountered in the topic. Other concept maps show a wider distribution of categories and educational practitioners need to take note of which types of difficulty (S, P or R) is likely to cause a given problematic link, so they can address it appropriately. In particular, difficulties with qualitative aspects of pH (Figure 9.10) and Brønsted acid-base reactions (Figure 9.7) concern either acid-base properties or representations. When learning about Arrhenius acid-base reactions (Figure 9.5) and strength (Figure 9.8) students may encounter difficulties in all three categories. From this summary, for many acid-base topics educators can anticipate certain categories of difficulties and plan accordingly.

In topics where propositional links are frequently associated with difficulties in overlapping categories the problem is further compounded, because several strategies may be needed to address one problematic conceptual link, as is typical of the multi-faceted nature of learning (Schönborn & Anderson, 2008a). Referring back to the analysis of all the troublesome propositions, Table 9.5 (see Section 9.3.1) showed that where propositions were implicated in more than one difficulty, the difficulties were usually limited to one category, with only 13% implicated in two or more categories. Therefore the frequency of overlaps shown in Figures 9.2 (25%), 9.4 (30%), 9.6(20%) and 9.8 (21%) are anomalously high. One must ask why? What is special about the topics in these concept maps?

The conceptual structure around acid-base species shows that an operational model (Figure 9.2) and Arrhenius model (Figure 9.4) inextricably link both examples and their properties, in accordance with a conceptual disciplinary structure as advocated by Herron (1996). However within the topic, the associated student difficulties were spread over both species (S) and properties or processes (P), with few representational (R) difficulties. In this regard, Solomonidou and Stavridou (2000) found student understanding matured from *inert substance* characterised by its uses, to the idea of *properties* and finally to *substances with perceptible properties* before students could understand that new substances were produced through *chemical change*.

Furthermore, few junior secondary students had reached the last stage (Johnson, 2002). Accordingly, students may not understand the idea of a classification of substances, by any means including uses (S difficulty) or they might not understand the idea of properties or a chemical reaction (P difficulty). Thus it can be argued that the type of difficulties encountered in an operational model of acid-base species are more psychological (i.e. due to cognitive development) than conceptual. Where more than one category of difficulty is associated with a particular proposition, all possible sources need to be considered. For example, students may not understand the reactions of the species which give rise to their properties, possibly because they do not understand the nature of a chemical reaction. Alternatively, they may not understand that these properties help scientists to recognise substances as examples of acid-base species (both P difficulties). Or perhaps more fundamentally the students do not understand the idea of a class of substances with characteristic properties (an S difficulty). For instance young students might not recognise cleaning agents as examples of basic substances because they do not know how to characterise bases according to properties rather than uses. Of further concern is that many of the links associated with both S and P categories of difficulties relate to cross-links to critical concepts as discussed above. The operational model of acid-base species and their properties is an important formative topic in students' conceptual development, but practitioners should not presume that it is simple. This critical analysis has shown it is highly complex. It can be speculated that in the Brønsted model (Figure 9.6) a similarly anomalously high proportion of overlapped difficulties (SP) arise from the same source.

Difficulties with qualitative aspects of pH can also have mixed sources; practitioners need to be aware that difficulty with a particular link may lie in the concepts concerning acid-base reaction processes (P difficulties) or the way in which chemists represent these processes (R difficulties). Awareness that there are two or more categories of difficulties prevalent with such important connections within acid-base topics should become part of practitioners' PCK.

The analysis of the distribution of categories of difficulties across acid-base topics (as distinguished by the concept maps) has shown that in some topics one category of difficulty predominates, and without further detail a practitioner could target knowledge in that category, and hope to address most common difficulties. In other topics, difficulties could fall into two or more categories and if practitioners do not address all categories, students may not master the relevant concepts. Practitioner PCK can be enhanced through awareness of the most likely categories of difficulties usually found in a topic, especially where they concern critical concepts or concepts that provide cross-links between topics, as in the previous section. Accordingly, the concept maps and set of propositional knowledge statements are a useful resource for practitioners.

9.4 SUMMARY AND DISCUSSION

This chapter sought to show whether the set of propositional knowledge statements derived through analysis of student difficulties reflected appropriate knowledge for teaching and learning acid-base models? In this regard the chapter has given an overview of the propositional knowledge which has been implicated in student difficulties. Furthermore the concept maps have been able to show not only the integration of the propositional statements but also their relationship to difficulties. The main outcomes of this chapter are as follows:

- The propositional statements derived to address student difficulties encompass the core but not all of a typical high school curriculum in acid-base chemistry.
- The propositional statements reflect knowledge necessary to understand three acid-base models in that they meet criteria of age-suitability, brevity, coherence within models, transparency of the hard-core of each model and acceptability to experts. They are thus suitable as a teaching resource.
- Of the propositional statements nearly 90% have been implicated in student difficulties. 74% of problematic propositions relate to specific difficulties, and 88% to a single category of difficulty.
- Within a particular topic, students sometimes encounter mainly one category of difficulty, although more commonly more than one category of difficulty will need to be addressed in a topic.
- Difficulties are more usefully categorized according to type of knowledge (concerning species, reaction processes or representations) rather than content structure. Teaching needs to target specific propositions within these categories.
- Concept maps identify concepts which are important for richly integrated understanding of the topic, as well as those with few links to prior knowledge. Understanding the models within this topic requires highly specific yet well integrated knowledge. All the critical concepts and cross-linked propositions have been implicated in student difficulties.

From these findings, the set of propositional knowledge statements and the concept maps are suitable resources for practitioners. They define the necessary knowledge as well as indicate potential difficulties which students may encounter. In this way they move a review of conceptions research from merely bibliographic to bringing “some conceptual and pedagogical coherence to findings that have been reported using different methods and very different contexts” (Erickson, 2000, p287). The analysis has identified the potential sources of cognitive difficulties and exposed the deeper basic assumptions of the topic as advocated by Nussbaum

(1998): "I think that we are at a stage in both the research literature on student conceptions and the emerging classroom-based literature on student learning in science where some serious consolidation of previous results needs to be undertaken." In this way it has contributed to educational practitioners' PCK, as follows.

They may be used in the following ways in planning what to teach, the sequence of teaching, the type of knowledge to focus on, and in assessment. Firstly when choosing what to teach, the hard core of each model is separated so that propositions can be introduced in the appropriate context, without mixing models. Practitioners can anticipate the explicit fine-grained propositional knowledge necessary for students to develop well integrated conceptions and plan accordingly. For instance, propositions indicate appropriate examples to show the breadth and limits to each model and the critical attributes in each definition. The sequence of teaching concepts can be determined from hierarchies in the concept maps which show direct and obvious links between concepts but also less direct links to ensure a rich interrelation of concepts. Furthermore critical concepts on the concept maps show where the topic can be focused, while cross-links indicate where one topic can provide points of entry to another.

Nearly every aspect of acid-base chemistry has potential student difficulties, which in many instances can be attributed to formal instruction (e.g. difficulties with mixed models). By referring to the summary of categories of difficulties, practitioners can pre-empt many of these. For instance if they expect difficulties with representations they can take care to make the meaning of chemical representations clear, whereas if they anticipate difficulties with species, then they need to focus of classifying characteristics. Particular difficulties regarding specific conceptual links can be foreseen and targeted through appropriately planned experiences. For instance to make associations between macroscopic observations and theoretical explanations, empirical activities need to be planned.

Concept maps can also inform assessment of integrated knowledge. Assessment exercises can be developed based on the links within and across topics. Alternatively, students may develop their own concept maps to reflect their own conceptual framework for a topic. While these will differ from those in Figures 9.1 to 9.11, practitioners may nevertheless use these figures as a guide to what is important and appropriate when evaluating students' concept maps.

In these ways the set of propositional knowledge statements and the concept maps, both indicating corresponding student difficulties are an important resource for teachers' PCK. Furthermore they could be used in developing curriculum material and textbooks. Finally, researchers who investigate student conceptions can make use of the propositions when defining their frame of reference. In particular, the many-to-one mapping between propositions and difficulties will be useful in developing items for concept inventories.

CHAPTER 10

CONCLUSIONS AND DISCUSSION

10.1 INTRODUCTION

This chapter will summarise the finding concerning each research question, considering firstly validity threats and limitations for the answers and then showing how these threats were addressed. Then the implications of the answers provided to the questions are discussed. I start with Research Question 1 (Chapter 5) and end with Research Question 5 (Chapter 9). However, I do not address the remaining research questions in turn because while each of Research Questions 2, 3 and 4 considered a different category of student difficulties, they were essentially parallel forms of: W*hat difficulties do students experience with acid-base chemistry?* They focused respectively on difficulties in the categories of acid-base species (Chapter 6), acid-base processes and properties (Chapter 7), and finally terminology and symbolism (Chapter 8). Each had similar sub-questions, and the same research methods were used for all three. Therefore in order to present an overview of the research findings, research Sub-questions 2a, 3a and 4a are discussed together, a similar format is followed for Sub-questions 2b, 3b and 4b, and then 2c, 3c and 4c. Finally the wider implications for the research findings for practitioners and researchers are discussed.

10.2 SCOPE OF THE RESEARCH ALREADY CONDUCTED

10.2.1 Introduction

Chapter 5 addressed the first research question: *What research has been already been conducted into student difficulties with acid-base chemistry?* By means of a wide range of search strategies, a considerable amount of published research on student conceptual difficulties could be identified. From this selection, 42 suitable reports were identified as suitable for the critical analysis, of which only three-quarters were identified through electronic searches. The process of the searching and screening was rigorous and transparent, with clear criteria being applied for inclusion and exclusion as recommended by Torgerson (2003) and Bennett *et al*. (2005a). Accordingly, it was possible to include all suitable publications which were available for critical analysis concerning the research on student difficulties with acid-base chemistry.

10.2.2 Main findings

There was a wide scope to the research, which included studies from 18 countries. This was judged to represent a wide variety of educational contexts, with many language groups. However, most of these were in Europe with minimal research on student cohorts in developing countries. Furthermore the largest amount of work was carried out among senior secondary students and there had been few studies on conceptions of tertiary or junior secondary students and almost none with elementary students. Laugksch (2002) found similar distributions of research cohorts in studies leading to higher degrees in science education in South Africa. Nevertheless the three models of acid-base chemistry chosen for the analysis are all relevant for senior secondary students so this body of research focused on a relevant age group.

Over half of the reports were from journals appearing in the ISI Science Citation Index and most of the remaining ones came from publications with a peer-review editorial process. Nevertheless, the quality of the research varied considerably, in terms of both research methods and depth of reporting. When trying to find exemplary papers concerning chemistry education research to illustrate the first aspect, Eybe and Schmidt (2001) also found similar problems of under-reporting, making it difficult to evaluate the methods used. From the analysis, guidelines for conducting research into student conceptions could be summarised. The range in quality of research had implications for the way in which descriptions of difficulties were synthesised.

10.3 THE DIFFICULTIES DESCRIBED IN ACID-BASE CHEMISTRY

10.3.1 Introduction

In Chapters 6, 7 and 8 the first research sub-question was: *What descriptions of difficulties with acid-base species (or properties or terminology and symbolism) can be synthesised from the existing research data?* The research carried out in this critical analysis has limitations because it is a secondary interpretation of student responses. However, in the analysis, all data from the reports were considered in the context of the original research. The data segments were extracted verbatim from the original publications and were left intact until the final descriptions were derived. Furthermore to avoid misrepresenting the research, the relevant parts of each report were reread as each difficulty was described in Chapter 6, 7 or 8. Where I have made my own speculations from the published information, I have made this clear and treated the description as only “suspected” or Level 1 unless further data was available. Consequently, the descriptions appear to be consistent with the original authors’ interpretations. Lincoln and Guba (1985) describe the outcome of qualitative research as “some level of understanding can be achieved” (p 37), and this analysis has achieved the outcome of a greater understanding of the research into student difficulties in acid-base chemistry.

A further limitation in the critical analysis is the lack of rigor shown in some of the original research. But validity is also a matter of degree rather than absolute (Cohen *et al.*, 2000, p 105), and the four-level framework was used to indicate the overall quality of the research leading to each difficulty description. For example Toplis (1998) (see Difficulty S5) does not report sufficient qualitative data to warrant classifying the difficulty description beyond emergent or Level 2. The four-level framework was also useful in indicating the generalizability of the results. Where the difficulty could be described in essentially the same manner across different contexts, educational and chemical, it was classified at Level 4, which implies that it is Established and likely to be found in other student populations.

10.3.2 Main findings

Through critical analysis, the contents of 42 publications have been distilled down to 53 difficulties, 14 of which had sub-difficulties. This large body of work belies the assertion by Wandersee, *et al.* (1994, p 181) that “the number of student alternative conceptions for a given science topic are relatively small”. However these authors may have anticipated Talanquer (2002; 2006) who showed that most difficulties in chemistry can be attributed to a small number of reasoning strategies. By contrast, Bucat (2004) argues that chemistry teachers will find topic specific results from applied research more useful than generic broad principles. As a result Bucat advocates documenting such specific PCK, as has been synthesised here through critical analysis. This synthesis will benefit practitioners in making the research more accessible than in a “plethora” of publications as advocated by Wandersee *et al*. (1994).

Of the difficulties described here, 10 concerned acid-base species, 26 were related to acid-base properties while 17 difficulties involved terminology or symbolism used to represent acid-base concepts. No age group is immune to difficulties; they have been reported mainly from senior secondary schools, but even at university, and also among teachers. Consequently, practitioners would be naïve to presume that older students have grown beyond these inappropriate ideas, as found by Salloum and BouJaoude (2008), or to overestimate students’ performance, as shown by Agung and Schwartz (2007). Difficulties synthesised through this analysis fall into two main groups: those due to inadequate practical experience and those due to models. Accordingly practitioners need to be aware of the extensive range of difficulties which students may experience with such central ideas. To this end some common problems and reasoning strategies across the categories of difficulty are discussed next.

10.3.2.1 Everyday applications

The practical relevance of acid-base chemistry escapes a number of students. In particular they see little relevance of acid-base chemistry in everyday applications (Difficulty S7) and they have a biased view toward the dangers of such substances (Difficulties P1 to P4). This latter idea can be attributed to ideas developed in primary school when the dangers of acids are discussed (Hand & Treagust, 1988). Teachers interviewed by these authors commented: “Maybe we shouldn’t emphasise the dangers of acids so much.” Along the same lines, Longfield (2006) describes educating her 3rd Grade students about the need for goggles and gloves. Instead of making their use a rule in all chemistry investigations, she impresses upon the class the need for safety precautions because the household vinegar that they will use is acidic, as demonstrated with pH paper. In this way, she makes a notable association between safety precautions and acids, rather than with all chemicals. A more realistic understanding can be achieved through conceptual conflict strategies based on empirical observations (Hand & Treagust, 1988; Demircioğlu *et al*., 2005).

With regard the everyday relevance of acid-base chemistry, Furió-Más *et al*. (2005) implicated school and university textbooks published in the USA and Spain as a problem, because they presented acid-base chemistry as “socially disconnected”. However, a meta-analysis of research into the effectiveness of teaching strategies in the USA showed the highest ranked effect to be an ‘enhanced context’ strategy that related student learning to previous experiences or knowledge (Schroeder *et al,* 2007). Rivet and Krajcik (2008) attribute such an effect, not only to the motivating factor of engaging students’ interest, but also to the context actually supporting learning. They argue that by providing students with a cognitive framework of prior ideas on which to anchor new ideas, the context enables students to organise their knowledge, make connections and differentiate concepts. However these results may not apply elsewhere, as Campbell *et al.* (2000) reported junior secondary students in Swaziland showed poor science-based reasoning used to solve an everyday problem which paralleled the reactions learned in class, despite having been taught in a context-based approach. This reinforces the need for conceptual research studies to also broaden the cohorts studied to those in less developed countries, as discussed in Section 10.2.

10.3.2.2 Theoretical models lack an empirical base

Some student difficulties indicate little integration of empirical experience with conceptual knowledge. In particular there are difficulties identifying physical and chemical properties of acids and bases (P4 to P9) as well as observing heat of reaction (P17), the non-neutrality of some end points (P16), hydrolysis effects of salts (P25) and the pH scale (P10 to P12). Such difficulties fall into Herron’s (1996) classification of ‘misconceptions’ as beliefs about phenomena that contradict empirical facts (see Section 2.2). These students appear to have not experienced these phenomena or do not remember them. Empirical experience is important for two reasons. In the first place it is an important aspect of conceptual knowledge – see memories of events (White & Gunstone, 1992) in Section 2.1.2. Furthermore theoretical models are historically based on empirical observations. This is reinforced by titles of historical chemistry publications, for instance: “Contribution of the theory of acid and base catalysis. The mutarotation of glucose.” (Brønsted & Guggenheim, 1927) and “The electronic theory of valency - Part IV. The origin of acidity” (Lowry, 1924). This remains so today, for both novices and experts: “Chemistry seems to be composed of a whole variety of modelling processes for a variety of purposes, but all related in linking macroscopic behaviours with sub-microscopic explanations” (Oversby 2000a, p 228). Because students often lack experiential links in their conceptions, they rely on simplistic reasoning as they meander through confusing theories. Accordingly students should be able to identify and give operational definitions for acids and bases as distinct substances, and understand the need for theoretical models to explain further observations. However student difficulties may lie with modern textbooks where theories are presented with little empirical background. In this regard, Furió-Más *et al.* (2005) found that 82% of the textbooks analysed did not us the macroscopic context to pose problems which theories were needed to answer. As long ago as 1936 some chemists were already concerned that “physical chemistry ... had caused chemistry to lose its tactile, sensuous base in the laboratory” (Brock, 1992, p 388). Similarly, modern university students appear to have lost touch with everyday experience; they seldom give ‘malleable and ductile’ as properties of metals, yet these are some of the very properties that theories of chemical bonding seek to explain (Laing, 1999). Macroscopic observations have not lost their relevance, despite the introduction of theoretical models.

10.3.2.3 Student difficulties with models

Models for acids and bases create many difficulties for students. The critical analysis has shown four ways that students deal with the various models in acid-base chemistry. Firstly, as already noted by Hawkes (1992), they do not accommodate new models, but simply fall back on the one learned first. This was evident in the many reports of students limiting their definitions of acids to operational rather than theoretical definitions (Difficulties S1.1 and S1.2), or in their retaining Arrhenius conceptions and ignoring Brønsted concepts (S2.3). Difficulties with the Brønsted conception of acids are not surprising. There is little evidence that students aged less than 17 years work comfortably and fluently with sub-microscopic chemical conceptions (Gabel, 1993). The non-particle view of matter is pervasive. Herron (1975) argues that students who have not yet reached Piaget’s formal operations stage (being able to think beyond concrete perceptions) will not be able to “conceive of an acid as a proton donor or electron pair acceptor” although using an operational definition that includes testing acids with litmus would be within their grasp. His estimate of 50% of students entering college chemistry not yet being at this stage is verified by Bradley *et al.* (1998) who found that only 66% of the Grade 12 students surveyed in South Africa were “particle thinkers”. In particular in Nakhleh (1994) found that senior secondary students tended to use a non-particulate model when depicting their conception of an acid ‘under a microscope’. The Brønsted model may be too abstract for the cognitive development of many students and the curriculum.

The students’ second strategy manifests when they consider earlier models as irrelevant, using only the latest one taught. This is shown in Difficulty S3, where students apply the Brønsted model to neutralization reactions between substances, whereas an operational model would be more appropriate. Carr (1984) emphasises that students need clear ‘signposts’ to show where one model is more applicable than another. For instance, experts know that an operational model concerns substances whereas the Brønsted model relates to particles, but this tacit knowledge is seldom made explicit for students.

Another tactic students use with multiple models is to create a hybrid model, incorporating aspects of each model into a personal mixture of ideas, as was evident in Difficulties S2.4, S4 and S5. In these, students use sodium hydroxide rather than the hydroxide ion as a Brønsted base, they amalgamate definitions from two models with consequent confusion, or they absorbed the term alkali from the operational and Arrhenius models into the Brønsted model. In essence, the three strategies above suggest that students conceive models as ‘one size fits all’, with a single model applicable across all contexts, as shown in Difficulty S3. This problem occurs more widely than in the acid-base context, as shown by an analysis of student conceptions in chemistry, from which Talanquer (2006) concluded that ‘commonsense learners’ believe in a one-to-one correspondence between models and reality. The problem is not limited to chemistry, and infers that students do not understand the nature of science (Justi & Gilbert, 1999). Their research showed that instead of understanding the different targets and background in each model, students simply viewed them as different “language” or “forms of expression” for the same concepts.

The critical analysis has revealed yet another strategy used by students. In Difficulty P24 students indicate that they know there were two acid-base models but apply them selectively – Arrhenius for strong acids and Brønsted for weak ones, instead of comparing weak and strong acids using criteria from one model. Besides Demerouti *et al*. (2004), there appears to be no other reports showing this strategy. Further research could show whether this is a liminal or transition state in their conceptions about models (Perkins, 1999).

The critical analysis of student difficulties concerning models provides confirmatory evidence for Carr's (1984) statement that student difficulties are "more usually perceived in terms of confusion about models used in teaching the concept than as a conflict between preconceptions and the scientific view". In a similar vein, Taber (2001a) argues that much of theoretical chemistry is about models rather than a hierarchy of concepts, and that many of the student difficulties are caused primarily by instruction in these models rather than pre-conceptions before instruction. Appropriate tuition in the different acid-base models demands that practitioners be aware of the differences between the models in order to make such knowledge clear for their students.

10.4 THE DEPTH OF RESEARCH IN CATEGORIES OF DIFFICULTIES

10.4.1 Introduction

In each of Chapters 6, 7 and 8 the second Research Sub-question addressed was: *How stable are these difficulty descriptions across different contexts?* To answer this question, the level of description for each difficulty was evaluated on a four-level framework (see Table 4.4 in Section 4.5.5.2). Because the body of research work on acid-base conceptions included a wide variety of educational and chemical contexts, many of the difficulties could be described at the highest level (Level 4 or Established). Table 10.1 below summarises the number of difficulties identified in each category according to the focus of the difficulty. It gives data only for the difficulties classified in the acid-base context. This means, for example, that difficulties such as that concerning the nature of the chemical reaction, which is more pervasive than simply acid-base chemistry, have not been included. Frequently acid and base versions of the same conception were described as sub-difficulties to reflect the different depth of research on the two aspects of the same conception (see Difficulty R12 Section 8.4.1.2). Accordingly, all sub-difficulties are included individually along with difficulties in the table below, making the total greater than 53, as reported in Section 10.3.2. The summary in the table which follows shows that, overall, difficulty descriptions are almost equally distributed through Levels 4, 3 and 2, with fewer at Level 1. However, there are two disparities in the distribution of research conducted; these concern the acid-base topics and the categories of difficulties, which are discussed next.

Table 10.1 Numbers of Difficulties or Sub-difficulties classified for each Category.

Category of difficulty or sub-difficulty	**Classification Level**	**acid**	**base**	**acid-base**	**Neutral**	**salt**	**TOTAL**
Acid-base species	4 Established	2	1	1	1		5
	3 Partially Established		2	2			4
	2 Emergent	1	2			1	4
total 15	1 Suspected				1	1	2
Acid-base properties	4 Established	4	1	3			8
	3 Partially Established	3	1	5		1	10
	2 Emergent	2	1	3		4	10
total 36	1 Suspected	3	1	3		1	8
Acid-base terminology and symbols	4 Established	1	1	3			5
	3 Partially Established	2	1	3	1		7
	2 Emergent	3	1	2			6
total 20	1 Suspected	1				1	2
	TOTAL	22	12	25	3	9	71

10.4.2 Difficulties which have been under-researched

The analysis in Table 10.1 shows firstly that many more difficulties have been identified which involve acids alone, than bases alone. In particular, only three conceptions of bases have received enough attention to warrant a Level 4 description in contrast with seven similarly classified for acids. A typical example is research showing that students confuse the term ‘strength’ used in acid-strength with bond strength (Difficulty R2 at Level 3+++) with nothing similar being reported for bases. While it is possible that students simply experience fewer difficulties with bases, this is unlikely as many researchers have noted students’ poorer conceptions of bases (e.g. Cros *et al.*, 1986; Nakhleh & Krajcik, 1994). Accordingly, it appears that researchers have fallen into the same trap as students, thinking that bases are somehow less important than acids. Student conceptions of bases have been under-researched.

The second anomaly shown in the table is that nearly half the difficulties with acid-base species have been established at Level 4, whereas less than a quarter of those in the other categories of properties or terminology and symbols have been taken to this level, and many difficulties in these categories languish at classification level 1 or 2, being merely suspected or emergent. These two findings confirm many authors’ assertions that research on student conceptions has too many dead ends with isolated, ad-hoc studies not being replicated (Sanders, 1993; Wandersee *et al.,* 1994; Krnel *et al.*, 1998; Jenkins, 2000; Grayson *et al.*; 2001; Kind, 2004).

As Grayson *et al.* (2001) asserted, the preponderance of uncoordinated investigations, sometimes on single student cohorts, hinders progress in developing accurate descriptions of specific student difficulties (Grayson *et al.*, 2001). Instead, individual studies need to be part of a continuum and in this regard, Sanders (1993) called for researchers to plan work that illuminates areas where answers are still lacking, rather than accumulating trivia. However, difficulties with low classifications are not necessarily trivial, for instance Difficulty S8 suggests that some students have little concept of the fundamental concept of neutrality (level 1) while Difficulty P23 (level 2) concerning the complementary relationship between strength of acid-base conjugates has implications for tertiary students understanding buffer systems (Orgill & Sutherland, 2008). There is evidently still much work still to be done in investigating student conceptions in order to describe them accurately; however until now, research has been focused more on species and less of other aspects of acid-base chemistry. I suggest two possible reasons for the bias. Firstly little work had been carried out on tertiary student cohorts (see Sections 5.2 and 10.2.1). By focusing on high school students researchers have also focused on central ideas of acid-base species rather than the more abstract aspects of their properties and reactions, or the way in which these are represented. Alternatively, researchers may have mirrored the cognitive development of novices, who find it easier to organise their knowledge around species, whereas experts tended to use processes such as chemical reactions as their theme (see Wilson, 1998, Section 4.3.2.4). In a similar way research into student difficulties tends to be organised around species rather than properties or more abstract representations. Now that research gaps have been shown, it remains to be seen whether once these are publicised the research community will rise to the challenge of addressing the gaps.

10.4.3 Difficulties which have been adequately or over-researched

As a corollary to the foregoing challenge, the current critical analysis has also identified 18 conceptions which can be described at Level 4. Two such descriptions arose through single sustained research projects (P16 and P20.2) and the remaining 16 descriptions arose by combining evidence from different research projects. Some of these have been previously recognised and the work cited by other authors, although only as individual studies, rather than as an aggregate of work with similar implications. Form this it appears that the value of synthesis of results from ad-hoc studies has not been recognised. For the 18 conceptions which have been described at Level 4, the research focus needs to move beyond merely describing or showing the existence of the conception to another focus, such as cross-age studies or teaching strategies to avert or remediate the difficulty. In this regard, the propositional knowledge alongside each difficulty will be valuable.

There are also student conceptions which have been over-researched. To illustrate, consider Difficulty P16 (Every neutralization reaction produces a neutral solution) which was published with sufficient research from one sustained study to classify it at Level 4 (Schmidt, 1991). Over the following 16 years eight more publications have reported its existence in student cohorts (Vidyapati & Seethramappa, 1995; Demerouti *et al*., 2004; Sheppard, 2006; Lin & Chiu, 2007; Chiu, 2007; Demircioğlu *et al*., 2004; Drechsler & Schmidt, 2005b; Pinarbasi, 2007). All of those since 1996 cite Schmidt's work, but in only the last three listed are the results interpreted in the light of his work. To illustrate, Drechsler and Schmidt (2005b) show another reason (besides Schmidt's description of *neutralization* as a 'hidden persuader') for the conception. According to their data, students assumed the solution became neutral because the reaction produced water so that in particular *water* seems to be tied to the concept of neutrality. By contrast, the remaining five publications give little further insight into a previously established conception. In particular, Lin and Chiu (2007) found that students used a 'character model' to predict the acidity, basicity or neutrality of a reaction endpoint. This meant that students relied on key Chinese characters, rather than scientific reasoning to arrive at their predictions. For example, the character for neutralization is similar to that implying mean, middle or neutrality; consequently, a student can mistakenly predict the result of any acid-base reaction to be neutral. This is similar to a 'hidden persuader' showing that the difficulty is not limited to Western languages, but Lin and Chiu (2007) made no mention of it. It can therefore be concluded that half the later research projects were ad-hoc studies, with no sense of adding complementary studies to a body of knowledge.

With a Level 4 description, a difficulty should have been included in review articles. Considering the number of authors given above who cite Schmidt (1991), the publication was easily obtained. It is, therefore, astonishing that this misconception is not mentioned in either Garnett *et al.*'s (1995) "more comprehensive review of the literature on alternative conceptions", or Kind's (2004) review that aimed to "bring together research on students' misconceptions in ... eleven conceptual areas [including acids and bases] in chemistry", mention. As Bennett *et al*. (2005b) assert, narrative reviews have been too subjective without comprehensive search methods and explicit inclusion/exclusion criteria. The current critical analysis fulfils the latter.

The manner in which Schmidt's (1991) description of the difficulty is quoted is not always consistent. To illustrate, two early reviews on chemical misconceptions have cited Schmidt's work, as follows:

> "Students applied the neutralization concept only for strong acids and bases and believed that neutralization reactions went to completion." (Gabel & Bunce, 1994)

> "Mixing an acid with a base (without regard to quantities) neutralizes the base resulting in a neutral solution." (Horton, 2001)

Gabel and Bunce appear to have extended Schmidt's description but it is still within the context of his investigation. In this regard, Schmidt (1991) argues that students reasoned by "assuming that neutralization is an irreversible reaction." However, the list of misconceptions edited by Horton introduces a completely new sense – Schmidt's work was clearly in the context of relative strength of acid and base, not in their relative quantities. Caution is needed when interpreting authors' knowledge claims. Accordingly, this shows another reason for presenting student misconceptions alongside the scientifically accepted propositions. Not only do the latter show conceptions educators would like students to have, but they give the chemical context of the study.

10.5 PROPOSITIONAL KNOWLEDGE

10.5.1 Introduction

In Chapters 6, 7 and 8 the third Research Sub-questions were respectively: *What statements of propositional knowledge are needed to address the difficulties with species in acid-base chemistry (or with acid-base properties or with acid-base terminology and symbolism)?*

In the initial critique of the quality of the research (Research Question 1) it was shown that 30% of the reports gave absolutely no indication at all of propositional knowledge which they considered scientifically acceptable and few authors gave an explicit theoretical framework as recommended by Treagust (1988) (see Section 5.3.2). This was a challenge when mapping data on student difficulties as I had to decide what appropriate propositional knowledge was relevant. To accommodate the problem, my interpretation of the required propositional knowledge was informed firstly by data on the difficulty itself, and then the chemical context investigated in original research. To this end I relied on my own pedagogical content knowledge gained through teaching experience in deciding what propositional knowledge related to a specific difficulty. Nussbaum (1998) considers this intuitive method to be an acceptable way of undertaking cognitive analysis of content (see Section 3.2.3.3). Moreover, I intentionally included more propositional knowledge than might be strictly necessary to address a particular difficulty. For instance, difficulty S6 concerning amphoteric species mapped to ten propositional statements. Furthermore, it appears that the number of propositional knowledge statements implicated in a difficulty does not decrease as more stable difficulty descriptions are achieved. For instance Difficulty R11 (described at level 4) maps to only two propositional statements, whereas R4 (Level 2) mapped to six statements. Therefore there was no suggestion that a higher level of difficulty description should infer fewer or more propositional statements. It is rather the complexity of the concept which determines the number of propositions implicated. In this way, I implicated propositional knowledge statements in each difficulty, but did not claim that they necessarily targeted the source of the difficulty. Accordingly, the propositional knowledge presented in this dissertation and summarised in Table 9.1 represents the minimum knowledge which students need in order to integrate concepts appropriately. Its suitability for teaching and learning is discussed in Section 10.6.

10.5.2 The value of the propositional knowledge statements

The process of reciprocal mapping showed 218 propositional statements were implicated in difficulties which students experience with acid-base chemistry. In the reciprocal mapping procedure, the propositional knowledge not only defined the frame of reference (as emphasised in Section 10.4.3) but in many cases also helped to hone difficulty descriptions. Because only about half the statements illuminated in the analysis came from literature published on student conceptions, it appears that the role of propositional knowledge in describing conceptions has been grossly undervalued. Furthermore, by means of comparison to propositional knowledge, four reported misconceptions were shown instead to instances of students' use of alternative acid-base models. Without such a framework, these had been erroneously classified as misconceptions. There was further value in the propositional knowledge when the set of statements were analysed in Chapter 9 as shown in Section 10.6.

10.5.3 The nature of the propositional knowledge statements

The propositional knowledge given here is not new; indeed it may seem obvious to experts. Experts know which model to use in each situation, they know the limitations of and appropriate representations for of each model, they move fluently between them according to the demands of the situation (Johnstone, 1982). In contrast, novices lack this knowledge and need it to be made explicit for them. In this regard, Hodson (1992) indicates the need for explicit instruction in communicating agreed conventions for analysing and interpreting events. Similarly, Bucat (2004) shows instances of PCK such as 'unpacking' the meaning of equilibrium constant. This is echoed by Treagust *et al.* (1996, p 4) who point out the absurdity of expecting "students to be able to construct science and mathematical conceptions without any guidance on the basis of their pre-existing conceptions alone". In this way all these authors affirm a constructivist principle of knowledge being socially mediated as when an educator assists in students understanding pre-existing scientific knowledge (see Section 3.2.1). Accordingly, instruction needs to focus explicitly on problematic propositional links, in order to avert difficulties (Muthukrishna *et al*., 1993), particularly with regard to non-intuitive concepts (de Vos & Verdonk, 1996; Schmidt, 1997; Oversby, 2000b) as commonly found in theoretical chemistry.

In order to make meaning of new knowledge, it is necessary to link it to pre-existing knowledge, which for experts may well be tacit knowledge. This analysis has shown that tacit knowledge is especially pertinent with respect to acid-base models, in particular their context, limitations and the modes of representation appropriate for each model. Some experts' tacit knowledge is mirrored in their teaching (Loeffler (1989). In particular, Rollnick *et al.* (2008) found that expert teachers with good subject matter knowledge could articulate the nuances of a topic, making it more accessible for students. However, experts might not have thought of making this knowledge overt for students as Orgill and Sutherland (2008) relate, concerning buffer solutions. This tacit knowledge and its connections need to be made overt for the student (although how this should be done is not part of the current research). Bucat's (2004) example above is one such instance, or as Ault *et al.* (1984) suggest – the simple statement: 'everything is made up of molecules' needs the added emphasis: 'and nothing else'. In the propositional knowledge I included similarly 'obvious' statements such as that suggested by Demerouti *et al.* (2004): "Water is present in aqueous solutions" (see Section 9.4.3.1). Teaching needs to make experts' tacit knowledge more explicit in order to facilitate novices making meaning of the topic, as I suggest in Figure 10.1 below.

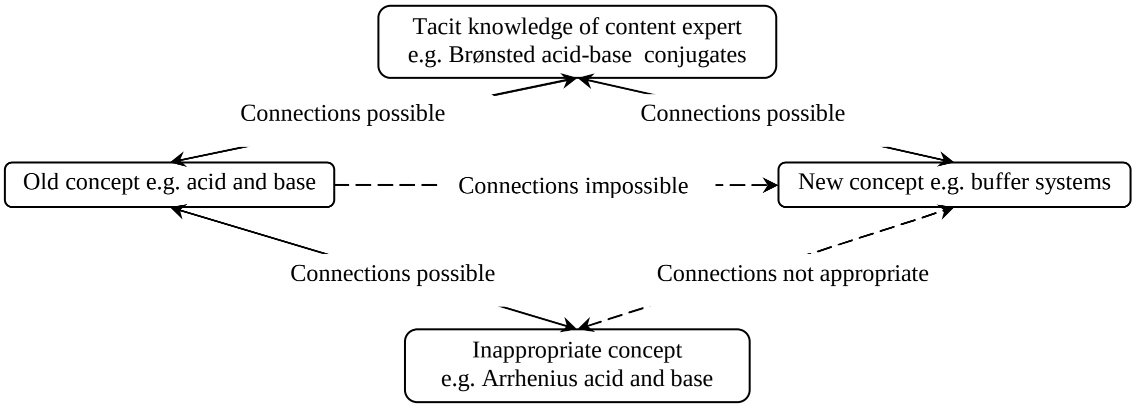

Figure 10.1 The role of tacit knowledge in making connections between concepts

This diagram indicates that experts can make connections between old and new concepts due to their tacit knowledge. The example in the diagram shows that to understand a buffer system requires knowledge that the acid and base are Brønsted acid-base conjugates. If this knowledge is missing, as can happen with novices, these conceptual connections are impossible resulting in fragmented understanding, as has been reported by Watters and Watters (2006). It indicates a limited propositional hierarchy (see Novak & Gowan, 1984, Section 2.4). However, what is more probable (in view of humans being ‘sense-makers’ as they construct knowledge, see Section 3.2.1) is that novices attempt to link new knowledge to inappropriate concepts, in this case familiar Arrhenius acids, leading to inappropriate connections, or propositional hierarchies (Novak and Gowan, 1984) found recently in the context of buffer systems (Orgill & Sutherland, 2008). In particular, there are few cross-links between the Brønsted model for acid-base reactions and other topics (see Section 9.3.2.2), so when learning this model, students may frequently seek links to inappropriate concepts from other models. A particular problem arises when the instructor and students have different models in mind. To amplify, for experts, the ‘default’ meaning for ‘acid’ is ‘Brønsted acid’ (Southway, pers. com.) but for novices it could mean the solution used in the laboratory last week. Or as described in Difficulty R2 (see Section 8.2.1.3) ‘strong acid’ may, for students, invoke an idea of strong bonds. Such a mismatch in the ‘default’ meaning is a potential source of confusion, and consequently novices are unlikely to integrate the new concept appropriately. The instructor needs to either find out what the students are thinking, or make the particular meaning for the word clear; in short, make tacit knowledge overt.

The incremental development of some of the propositional statements illustrates a cycle of making more tacit knowledge overt with further iterations of comparison to difficulties. For example an interim version of statement 2.1.1.6.2 is used for Difficulty S1.1 and the final one for P19 (see Tables 6.1 and 7.1). De Vos and Verdonk (1987a) describe a similar process in response to student feedback when developing a teaching sequence on the nature of chemical reactions. This illustrates the contribution to PCK which is made through the reciprocal mapping of student difficulties as an input into curriculum design. Reflective practitioners who respond sensitively to their students may adjust their teaching each year in a similar manner, but such experiential insight is often not shared and Bucat (2004) laments that it is lost when a teacher retires. Here the subject content has been repackaged in fine detail, recorded and available for all practitioners – a ready-made ‘slice’ of pedagogical content knowledge based on both teaching experience and research.

10.6 THE SUITABILITY OF THE PROPOSITIONAL STATEMENTS FOR TEACHING AND LEARNING

In Chapter 9, the final research question was considered, as follows: *Do the set of propositional knowledge statements derived through analysis of student difficulties reflect appropriate knowledge for teaching and learning acid-base models?* In answering this question the set of propositional statements together with the concept maps onto which they were integrated were evaluated with regard to their suitability as curriculum acid-base models and their usefulness in teaching and learning.

There are three possible limitations to the processes of deriving and analysing the set of propositional knowledge. The first concerning the personal choice of what particular propositional knowledge was implicated in each difficulty was already discussed in Section 10.5. A second possible limitation concerns the choice of category into which each difficulty fell, that is species, properties or representations (terminology and symbols). In this regard, reasons for the initial choice of categories were given in Section 4.2.4, and the appropriateness of this categorisation was verified by only about half of the 27% of the propositional statements which mapped to more than one difficulty being associated with difficulties across more than one category (see Section 9.3.1). The third limitation is the concept maps constructed to show the interrelations between the concepts. These are my personal representations of the relationships. However, the task required deep interaction with the concepts and the chemistry literature as shown by an average of 4 to 5 drafts for each map. In these processes, links were typically added or adjusted, rather than removed. Accordingly, the concept maps probably under represent the complexity of the topic rather than over represent it. This infers that there could be more critical nodes and cross links than those identified in Sections 9.3.2.1 and 9.3.2.2. Accordingly, the main research findings in Chapter 9 need to be treated as provisional in that they do not provide all the implications for teaching and learning. As the method of mapping difficulties to propositional knowledge has not been reported, these findings have also not been reported elsewhere.

As shown in Section 2.1, it is naïve to presume that propositional knowledge is not contentious. Accordingly, the acceptability of the propositional statements themselves was governed by pre-determined criteria (see Sections 4.6.1 and 9.5.2) To this end they were checked for internal consistency of each model by means of the concept maps and compared with historical and modern chemistry sources, chemistry education literature, and finally deemed acceptable to two expert chemists. There is no claim that the propositional statements derived to address student difficulties are a comprehensive list of all that students should know (as in a curriculum statement). As shown in Section 9.2.1, they do reflect the core but not all of a typical high school curriculum in acid-base chemistry. Importantly they show potentially “troublesome knowledge” (Perkins, 1999). Therefore they are suitable for teaching and learning acid-base chemistry but will need to be supplemented according to particular curricular requirements. As 90% of the propositional statements were derived in response to student difficulties, a large part of the knowledge base for acid-base chemistry is potentially problematic. Consequently understanding these concepts is not simple, despite their appearance in junior primary and even elementary school curricula. This contrasts with the teacher surveys discussed in Section 2.5.2 which showed they thought the topic was either undemanding or had mainly mathematical difficulties. It does however explain the feelings of fear and frustration among students reported by Tarr and Norwell (1985) (see Section 2.5.2).

The specific nature of the mapping between student difficulties and propositional knowledge statements (75% of problematic propositions relate to specific difficulties) indicates that there is usually a many-to-one mapping. Thus where a problematic conceptual link is identified in students, three quarters of the time this will predict which difficulty will ensue, and appropriate remedial action may be taken. It does not unfortunately work in reverse. Targeting one problematic link will not necessarily remediate or avoid the difficulty as more than one problematic conceptual link may be involved with the difficulty.

The appropriateness of the categories of species, properties or reaction processes and representations as terminology or symbols means that practitioners who do not have sufficient teaching time to target each specific conceptual link can instead focus on the type of knowledge which is most often implicated in a topic, as shown on the relevant concept maps. For example if they anticipate mostly representational difficulties they might focus explicit teaching on the subtleties of the representations used. In a similar way, in the topic of chemical equilibrium, Bucat (2004) highlights the difference between *constant* meaning *remains the same for a given system*, and *a constant* meaning the *same value for any system*. Finally the integration between most topics is evident from the concept maps. In this regard, Oversby (2000a) has noted that textbooks seldom relate one chapter (such as bonding) to another (such as acids and bases). However, the curriculum could also be at fault in that it expects students to use chemical formulae in acid-base chemistry before they understand the arrangement of atoms that allow such species to be proton donors, or easily dissociated. For example, Nicoll (2003) found many undergraduate students thought that formaldehyde (CH_2O) had a structure of a water molecule with a carbon atom attached. Furthermore the Brønsted model provides few links to prior knowledge. For this reason, educators need to ensure it is grounded in macroscopic observations as discussed in Section 10.3.2.2. Laing (1999) and other chemistry education writers (see Section 2.3.3.) have noted that modern chemistry curricula frequently focus on theoretical aspects at the expense of more empirical work.

10.7 IMPLICATIONS OF THE RESEARCH

The results of the critical analysis of research on into student difficulties with acid-base chemistry have implications for both educational practitioners and researchers.

10.7.1 Implications for Practitioner Pedagogical Content Knowledge (PCK)

The pedagogical content knowledge represented by three aspects: descriptions of students difficulties, the finely divided propositional knowledge reflecting expert tacit knowledge and the concept maps which integrate the two, is a resource for practitioners at all levels, teachers, curriculum developers, and textbooks authors.

The literature review showed that frequently teachers are unaware of student conceptual difficulties (see Section 2.4.4). Furthermore they might not be aware that they themselves have conceptions which are not in accord with accepted science (Furió -Más *et al.*, 2005). These authors have also identified conceptual change in teachers as one of the most important trends in science education research. Hence the lists of student difficulties and propositional knowledge statements are a useful source for discussion among student teachers.

Teachers may know their subject matter, but teaching it is more complicated. Taber (2001c) asserts that many chemistry difficulties are caused primarily by prior instruction which Furió *et al.* (2002) see as a didactic rather than student difficulty. The didactic problem also involves textbooks, and these have been frequently implicated in causing difficulties, particularly with respect to models (see Section 2.3.4). Effective learning requires effective teaching, as according to Johnson *et al.* (2007), students of all abilities tend to achieve better when taught by the most effective teachers. They define effective teachers as those making use of well designed, purposeful and highly engaging instruction that is artfully implemented with flexibility according to students' needs and thereby meaningful to the students. Furthermore Arzi and White (2008) also show that experienced teachers' content knowledge has a specific nature. Firstly it has rich intradomain and interdisciplinary links, while at the same time being fine-grained, with important detail. Thus it is both wider and deeper than that of an academic researcher in the field. These authors also showed that teachers' subject matter knowledge changes during the course of their careers, being strongly influenced by curriculum materials. It follows that a prerequisite for improving chemistry learning is to have excellent teachers, excellent teachers are aware of their students' needs and difficulties, and have excellent subject-specific knowledge which needs to be fine-grained. This subject-specific knowledge is largely gleaned from curriculum materials. In a similar way the list of propositional statements has become more and more fine-grained with analysis of further student difficulties. It therefore represents the cumulative experience of expert chemists, chemistry education research and teaching experience. It will have the most influence in raising the standard of teaching and learning acid-base chemistry if used in curriculum materials.

The effectiveness of reformed curriculum materials rests in part on the knowledge of student difficulties and their relationship to accepted propositional knowledge. The need to have models differentiated for teachers is just as great as it is for students. In particular curriculum materials such as textbooks need to address the following aspects:

- Using empirical observations; firstly to contextualise acid-base concepts and then to provide reasons for introducing successive models.
- Signposting the differences between acid-base models, that is their appropriate contexts and limitations, partly by means of non-examples as well as appropriate examples.
- Avoiding hybrid models, by keeping examples, terminology and symbolism appropriate for each model.
- Making explicit the tacit knowledge shown in this analysis.
- Giving bases the prominence they deserve alongside acids.
- Showing cross-links to prior knowledge, either in the acid-base topic or across other chemistry topics, such as bonding and chemical equilibrium.

Before any of this can take place, results from this analysis must be publicised. Too often researchers address only themselves so that research is published and then ignored (Jenkins, 2000) or lies forgotten in theses (Anderson, pers.com.) To this end the CARD website (http://www.card.unp.ac.za) is a useful international forum.

10.7.2 Educational implications of threshold concepts

A further use for these two sets of results – the concept maps and the descriptions of difficulties may be used to indicate which concepts are threshold concepts. Using two such inputs, Park and Light (2009) were able to identify two aspects of the quantum atomic model which were threshold for understanding it. Threshold concepts are those concepts which allow students to see a field of knowledge in a new way. Usually once the student understands the concept, the advances are irrevocable; it gives them a new way of seeing.

Land *et al*. (2006) advance the idea of a rhizomorphic curriculum structure, wherein there several ways of looking at the same concept. These provide points of entry to a common goal of understanding threshold concepts. In these authors' opinion this is more realistic than a strictly hierarchical structure as supported by Herron (1996). In this regard, acid -base chemistry is one such point of entry whereby students understanding of the nature of a chemical reaction in terms of new products formed, energy changes occurring in a reaction, chemical equilibrium. Similarly students learning about acid-base properties may gain entry to the concept of chemical classification by characteristic properties.

10.7.3 Cognitive development and the Brønsted model

Drechsler (2007) reported that students clearly did not understand the Brønsted model. This stands to reason as it is a process rather than species model. This analysis has shown a much larger number of difficulties concerning acid-base processes than acid-base species. It is also an unsurprising observation as it involves acid-base particles rather than substances. Consequently students need to engage with chemistry on a sub-microscopic level (see Section 2.3.3.), but as Section 10.3.2.3 showed, few are cognitively ready to do this even on entering tertiary education. Furthermore the analysis of difficulties shows that frequently these theoretical ideas are not shown as explaining macroscopic observations. The Brønsted model may be too abstract for the cognitive development of many high school students

10.8 IMPLICATIONS FOR FURTHER RESEARCH

10.8.1 Acid-base topics to research

For the research community, the research here presents some unanswered questions. This synthesis shows that some difficulties with acid-base models have been inadequately researched. Where research has not yet led to a stable description of a difficulty, or established that it occurs across multiple contexts, further investigation into its nature is needed.The difficulties with Level 3 descriptions may only need confirmatory studies in other chemical or educational contexts to hone the descriptions. Those with lower classifications first need exploratory studies, before probes become more focused. Broadly, there is no yet enough known about how many acid conceptions that have been identified which might also relate to bases. Because bases are conceived so differently in the Arrhenius and Brønsted models researching these conceptions will undoubtedly provide greater insight into difficulties which students experience with the model. By the same token further research is needed into more complex conceptions beyond definitions and examples. In particular very little research has shed light on how and why students represent sub-microscopic species interacting during acid-base reaction. The more demanding task of investigating conceptions of acid-base processes or representations of these might entail subtle research probes, as for example Schmidt (1991; 1995 & 1997). Such research may also need visual probes depicting sub-microscopic representations of the acid-base systems. Such visual data fell outside the criteria (verbal quotations) used to screen publications for this study (see Section 4.4.1). However it is notable that only four publications (that is less than 10%) of those accepted into this study (Nakhleh, 1994; Smith & Metz, 1996; Bradley & Mosimege, 1998; Sheppard, 2006) reported also using visual probes to gain insight into how students actually visualise acid-base processes. Such probes have been used for other chemistry topics (e.g. Kozma & Russell, 1997; Treagust & Mamiala, 2003; Nicoll, 2003; Stains & Talanquer, 2007; 2008). In particular, Halakova and Proksa (2007) developed visual items to parallel the descriptive items in the chemical concept inventory (Mulford & Robinson, 2002).

With the benefit of now having 18 problematic conceptions with Level 4 descriptions, these can feed into other types of research. For example, strategies by which difficulties can be reversed or even avoided (as suggested by Schmidt, 1997) should be designed and evaluated. Furthermore Çalyk *et al*. (2005) argue for going beyond merely documenting misconceptions into categorizing and interpreting them into diagnostic treatment or a theory building model of how to facilitate students' constructing scientific knowledge from their current conceptions. For instance Palmer (2005) showed that confronting alternative conceptions through the use of a reputational text was more effective in promoting conceptual change than was a merely didactic text: would this also be applicable for some of the acid-base difficulties?

Alternatively the place of the Brønsted model in the curriculum should be investigated. Is it too abstract for most school students as Herron (1975) argues, and has been suggested by this research? There is little evidence that students aged less than 17 years work comfortably and fluently with sub-microscopic chemical conceptions (Gabel, 1993; Brosnan & Reynolds, 2001) and a cross-age study would be useful in the context of acid-base models. Such a study relating to the particle nature of matter was carried out whereby Brosnan and Reynolds (2001) found out at what level students were operating through posing statements and asking if they "made sense" or not to the students. A similar study could show at what age students were operating comfortably with each acid-base model, and hence when these could be most meaningfully taught.

10.8.2 Concept inventories

The usefulness of concept inventories is being increasingly recognised (Howitt *et al.*, 2008). These 'banks' of conceptual multiple-choice questions are useful in evaluating student understanding pre- and post-instruction (see Section 2.4.1). There are currently few topics where a comprehensive and reliable bank of items has been developed. The force concept inventory (Hestenes *et al.*, 1992) was developed after 10 years research into physics conceptual difficulties (Grayson *et al.* 2001) but there are few available in chemistry (e.g. Mulford & Robinson, 2002; Halakova & Proksa, 2007), and almost none in biochemistry (Howitt *et al.*, 2008). Through such an inventory it is possible to (i) evaluate (or self-evaluate) teacher content knowledge (ii) identify potential stumbling blocks for their students; (iii) determine the level of functioning of students. The distractors used in concept inventory items are often based on descriptions of common student difficulties and Level 4 difficulty descriptions are imminently suitable for this. Furthermore the specific many-to-one mapping between propositions and difficulties also suggests specific distractors which can be used for new items. The many-to-one mapping found in this study was quite unexpected and further research could show whether it is specific to acid-base chemistry, perhaps due to the way I derived the propositional statements and categories of difficulties, or whether it is a general trend that identifying a specific problematic propositional link can indicate a specific difficulty.

10.8.3 Implications for research methods in conceptions research

This critical analysis has highlighted several important roles for a set of propositional knowledge statements in research concerning student conceptions. In the first place it defines a frame of reference for the study, and will inform the type of probe used in the research. If researchers wish to probe whether students understand aspects of a particular model they would be wise to make this requirement clear to students; the researchers' frame of reference needs to be made overt. In this way researchers would avoid assuming that the student knew which model was 'acceptable' to the researchers (falling themselves into the one-model-fits-all trap) and so deeming alternative models to be 'misconceptions'. Furthermore, researchers need to be especially careful of not, themselves, falling into a trap of hybrid models, and switching terms such as *species* and *substance*, or *ionization* and *dissociation* between models.

If instead researchers wish to find out which model the student is most comfortable with (as suggested in the previous section) propositional knowledge statements provide a framework on which to 'hang' student responses to more openly phrased questions. Thus, it is essential to put the propositions forward for comparison. This method of comparison has been used here to help group data segments on difficulties and then to sharpen the descriptions of the difficulties. In this way it has been possible to illuminate at least some of the propositional knowledge which is missing or inappropriate and so inhibiting scientific understanding.

Propositional knowledge statements serve a third role when they help define the context of a difficulty description when it is published, and so avoid it being misrepresented in other publications (see Section 10.4.2). Researchers cannot assume the propositional knowledge is not contentious; it is debatable so need to be stated. Furthermore it needs to be referenced from reliable sources, and checked against chemistry publications or expert opinion, or both. It is most important to have these propositional statements in conceptions research so that all persons (researchers, students, readers) are familiar with the frame of reference.

Most importantly, the method of searching, screening and comparative analysis of published research data on conceptual difficulties with propositional knowledge has been productive in the acid-base topic. There is little reason to suggest that it should not be used elsewhere in a similar manner. Appropriate reviews could provide the missing link between conceptual studies and curriculum or pedagogic reform. There is, however, a caveat. At the outset I was completely naïve about the volume of data that 42 reports would generate, despite advice from Bennett *et al*. (2005b), and in retrospect a much sharper focus for the critical analysis than acid-base chemistry would have been more manageable. A narrower topic such as pH or acid-base strength alone would have borne enough fruit.

REFERENCES

Abel, S. K. (2008). Twenty years later: does pedagogical content knowledge remain a useful idea? *International Journal of Science Education*, 10(13), 1405-1416.

Abimbola, I. O. (1988) The problem of terminology in the study of students' conceptions in science. *Science Education*, 72, 175-84

Agung, S. & Schwartz, M. S. (2007) Students’ understanding of conservation of matter, stoichiometry and balancing equations in Indonesia. *International Journal of Science Education*, 29(13), 1679-1702.

Anderson, T. R. (2007). Bridging the education research – teaching practice gap: The power of assessment. *Biochemistry and Molecular Biology Education*, 35(6), 471-477.

Anderson, T. R. & McKenzie, J. (2002) Using a meta-analysis to develop a database of students’ conceptual and reasoning difficulties. In C. Malcolm & C. Lubisi (Eds) *Proceedings of the 10th Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education, Durban.*

Anderson, T. R. & Schönborn, K. J. (2007). Bridging the education research – teaching practice gap: The importance of bridging the gap between science education research and its application in biochemistry teaching and learning: barriers and strategies. *Biochemistry and Molecular Biology Education*, 35(6) 465-470.

Anderson, T. R. & Schönborn, K. J. (2008). Bridging the education research – teaching practice gap: The multi-faceted nature of expert knowledge. *Biochemistry and Molecular Biology Education*, 36(4) 309-315.

Andersson, B. (1986) Pupils’ Explanations of Some Aspects of Chemical Reactions. *Science Education*, 70(5), 549-563.

Andersson, B. (1990) Pupils’ conceptions of matter and its transformations (age12-16). *Studies in Science Education.* 18, 53-85.

Arrhenius, S. (1903). *Development of the theory of electrolytic dissociation.* Nobel lecture http://nobelprize.org/nobel_prizes/chemistry/laureates/1903/arrhenius-lecture.pdf

Arrhenius, S. (1912). Electrolytic Dissociation. *Journal of the American Chemical Society*, 34(4), 353-364.

Ault, C. R., Novak, J.D. & Gowan, D. B. (1984). Constructing Vee maps for clinical interviews on molecule concepts. *Science Education*, 68 (4), 441-462. Cited by Taber (2001c)

Arzi, H. J. & White, R. T. (2008). Change in teachers’ knowledge of the subject matter: A 17-year longitudinal study. *Science Education*, 92(2), 221-251.

Badderly, A. (1986). *Working Memory* Oxford University Press. Oxford.

Banerjee, A. C. (1991). Misconceptions of students and teachers in chemical equilibrium. *International Journal of Science Education,* 13(4), 487-94.

Barrow, L. H. (2000) Do Elementary Science Methods Textbooks Facilitate the Understanding of Magnet Concepts? *Journal of Science Education and Technology*, 9(3), 199-205.

Bell, R. P. (1969). *Acids and bases,* Methuen, London.

Bennett, J., Campbell, B., Hogarth, S. & Lubben, F. (2005a). A systematic review of the effects on high school students of context-based and science-technology-society (STS) approaches to the teaching of science. in C. Kasanda, L. Muhammed, S. Akpo & Ngolo (Eds) *Proceedings of the Conference of the Southern African Association of Research in Mathematics, Science and Technology Education,* Windhoek

Bennett, J., Lubben, F., Hogarth, S. & Campbell, B. (2005b). Systematic reviews of research in science education: rigor or rigidity? *International Journal of Science Education,* 27(4), 387-406.

Bennett, J., Lubben, F., Hogarth, S. (2007). Bringing science to life: a synthesis of the research evidence on the effects of context-based and STS approaches to science teaching. *Science Education.* 91(3), 347-370.

Benson, D. L. Wittrock, M. C. & Baur, M. E. (1993). Students' preconceptions on the nature of gases. *Journal of Research In Science Teaching,* 30, 587-597.

Ben-Zvi, R, Eylon, B & Silberstein (1986). Is an atom of copper malleable? *Journal of Chemical Education,* 63(1) 64-66

Ben-Zvi, R, Eylon, B and Silberstein, J (1988) Theories, principles and laws. *Education in Chemistry,* 25(3), 88-92.

Black, P. J. & Lucas, A.M. (Eds) (1993). *Children's informal ideas in science*. Routledge, London.

Blosser, P. E. (1987). Science misconceptions research and some implications for the teaching of science to elementary school students. ERIC/SMEAC *Science Education Digest,* http://www.eric.ed.gov/ERICDocs/data/ericdocs2sql/content_storage_01/0000019b/80/30/4e/6c.pdf [Retrieved 15th March 2009]

Bodner, G. M. (2004). Twenty years of learning: how to do research in chemical education. *Journal of Chemical Education*, 81(5), 618-625.

Boo, H.-K., & Watson, J. R. (2001). Progression of high school students' (aged 16 – 18) conceptualizations about chemical reactions in solution. *Science Education,* 85(5), 568-585.

Botton, C. (1995) Collaborative concept mapping and formative assessment key stage 3: Understandings of acids and bases. *School Science Review*, 77(279), 124-130.

Bradley, J. D. & Brand, M. & Gerrans, G. C. & Harris, E (1998). Stages of development in student's concepts about macroscopic properties and microscopic structure of matter: an analysis of data from five South African secondary schools. *South African Journal of Chemistry,* 51(2), 85-91.

Bradley, J. D. & Mosimege, M. D. (1998). Misconceptions in acids and bases: a comparative study of student teachers with different chemistry backgrounds. *South African Journal of Chemistry,* 51(3), 137-145.

Brady, J.E. & Holum, J.R. (1993). *Chemistry: The study of matter and its changes.* Wiley, New York.

Brock, W.. H. (1992). *The Fontana History of Chemistry*. Fontana Press, London.

Brønsted, J. N. (1923). Some Remarks on the Concept of Acids and Bases. *Recueil des Travaux Chimiques des Pays-Bas,* 42(7), 18-828. http://chimie.scola.ac-paris.fr/Sitedechimie/hist_chi/text_origin/bronsted/Bronsted-Article.htm [Retrieved 31st October 2008].

Brønsted, J. N. (1926). The acid-base function of molecules and its dependency on the electric charge type. *Journal of Physical Chemistry,* 30, 777-790.

Brønsted, J. N. & Guggenheim, E. A. (1927). Contribution of the theory of acid and base catalysis. The mutarotation of glucose. *Journal of the American Chemical Society*. 49, 2554.

Brosnan, T. & Reynolds, Y. (2001). Student's Explanation of Scientific Phenomena: macro and micro differences. *Research in Science and Technology Education,* 19(1), 69-78.

Brown, J. S., Collins, A. & Duguid, P. (1989). Educational Researcher, 18(1), 32-42.

Browne, M. N. & Keeley, S. M. (2004) *Asking the right questions: A guide to critical thinking (7th ed).* Pearson Education Upper, Saddle River.

Bucat, R. (2004). Pedagogical content knowledge as a way forward: applied research in chemistry education. *Chemistry Education: Research and Practice,* 5(3), 215-228. http://www.uoi.gr/cerp/2004_October/pdf/04Bucat.pdf [Retrieved on 7th March 2009]

Bunce, D. M. (2001). Does Piaget still have something to say to chemists? Journal of Chemical Education, Online Symposium: Piaget, Constructivism and Beyond. *Journal of Chemical Education,* 78

Bunce, D .M. & Robinson, W. R. (1997) Research in Chemical Education – the third branch of our profession. *Journal of Chemical Education,* 74(9) 1076-1079

Burns, J. R. (1982). *An evaluation of the 6th and 7th form chemistry in terms of the needs of the students and the community*. Report to the Department of Education, Wellington, New Zealand, 1982, pp 96-100 [Cited by Carr (1984)]

Çalyk, M., Ayas, A. & Ebenezer, J. V. (2005). A review of solution chemistry studies: insights into students' conceptions. *Journal of Science, Education and Technology*, 14(1), 20- 50.

Camacho, M. & Good, R. (1987) Problem solving and chemical equilibrium: successful versus unsuccessful performance. *Journal of Research in Science Teaching*, 26(3), 251-272

Campbell, B., Lubben, F. & Dlamini, Z. (2000) Learning Science through Contexts: helping pupils make sense of everyday situations. *International Journal of Science Education*, 22(3), 239-252.

Cantu, L. L. & Herron, J. D. (1978). Concrete and Formal Piagetian Stages and Science Concept Attainment. *Journal of Research In Science Teaching*, 15(2), 135-143.

Carr, M. (1984). Model confusion in chemistry. *Research in Science Education*, 14, 97-103.

Carvalho, P. S. & Sampaio e Sousa, A. (2006). Should We Use Colours as Symbolic Representations of Hot and Cold? *Physics Education*, 41(3), 263-266.

Cassels, J. R. T. & Johnstone, A. H. (1983). The meaning of words and the teaching of chemistry. *Education in Chemistry*, 20(1), 10-11.

Chiu, M.-H. (2005). A national survey of students' conceptions in chemistry in Taiwan. *Chemical Education International*, 6 (1), 2005 from www.iupac.org/publications/cei [Retrieved 9th June 2006]

Chiu, M.-H. (2007). A national survey of students' conceptions in chemistry in Taiwan. *International Journal of Science Education*, 29(4), 421-452.

Chiu, M.-H., Chorng-Jee, G. & Treagust, D. F. (2007). Assessing students' conceptual understanding in science: An introduction about a national project in Taiwan. *International Journal of Science Education*, 29(4), 379-390.

Clark, M. W. (1928). *The determination of hydrogen ions (3rd ed).* Williams & Wilkins, Baltimore, in Jensen (2004)

Clerk, D. & Rutherford, M. (2000) Language as a confounding variable in the diagnosis of misconceptions. *International Journal of Science Education*, 22(7), 703-717.

Clifford, P. (2002). The pressure-flow hypothesis of phloem transport: Misconceptions in the a-level textbooks. *Journal of Biological Education*, 36(3), 110-112.

Cohen, L., Manion, L. & Morrison, K. (2000) *Research methods in education (5h ed).* Routledge Falmer, London.

Colman, A. M. A. (2001). *A Dictionary of Psychology*, Oxford University Press, Oxford.

Costa, N., Marques, L. & Kempa, R (2000). Science teachers' awareness of findings from educational research. *Chemistry Education: Research and Practice*, 1(1), 31-36. http://www.uoi.gr/cerp [Retrieved 7th June 2007]

Cropper, W. H. (2001). *Great Physicists*. Oxford University Press, Oxford.

Cros, D., Chastrette, M., & Fayol, M. (1988). Conceptions of second year university students of some fundamental notions in chemistry. *International Journal of Science Education,* 10(3), 331-336.

Cros, D., Maurin, M., Amouroux, R., Chastrette, M. & Leber, J. (1986). Conceptions of first year university students of the constituents of matter and notions of acids and bases. *European Journal of Science Education,* 8(3), 305-313.

Davis, J. B. (1953). Ammonia and "ammonium hydroxide". *Journal of Chemical Education,* 36(10), 511.

De Jong O. (2004). Crossing the borders: Chemical education research and teaching practice. *University Chemistry Education*, 4(1), 29-32. http://www.rsc.org/pdf/uchemed/papers/2000/41_dejong.pdf

de Jong, O. (2005) Research and Teaching practice in chemical education: Living apart or together? *Chemical Education International* 6(1) 1-6. http://old.iupac.org/publications/cei/vol6/10_De_Jong.pdf [Retrieved 8th March 2009]

de Jong, O. & van Driel, J. (2001). The development of prospective teacher's concerns about teaching chemistry topics at a macro-micro-symbolic interface. In Behrendt *et al.* (Eds) *Research in science Education – PAST Present and Future* pp 271-276. Kluwer Publishers, Dordrecht.

de Vos, W. & Pilot, A. (2001). Acids and Bases in layers: The stratal structure of an ancient topic. *Journal of Chemical Education*, 78(4), 494-499.

de Vos, W. & Verdonk, A. (1985a). A new road to reactions Part 1. *Journal of Chemical Education,* 62(3), 238-240.

de Vos, W. & Verdonk, A. (1985b). Roads to reactions Part 2. *Journal of Chemical Education,* 62(8), 648-649.

de Vos, W. & Verdonk, A. (1986). Roads to reactions Part 3. Teaching the heat effect of reactions. *Journal of Chemical Education,* 63(11), 972-974.

de Vos, W. & Verdonk, A. (1987a). Roads to reactions Part 4. The substance and its molecules. *Journal of Chemical Education,* 64(8), 692-694.

de Vos W. & Verdonk, A. H. (1996). The particulate nature of matter in science education and science. *Journal of Research in Science Teaching*, 33(6), 657-664.

Demerouti, M., Kousathana, M. & Tsaparlis, G. (2004). Acid-base equilibria, Part I. Upper secondary student's misconceptions and difficulties. *The Chemical Educator,* 9, 122-131.

Demircioğlu, G., Ayas, A. & Demircioglu, H. (2005). Conceptual changes achieved through a new teaching program on acids and bases. *Chemistry Education Research and Practice,* 6(1), 36-51. http://www.rsc.org/images/p3_Demircioglu_tcm18-31135.pdf [Retrieved 31st March 2009]

Demircioğlu, G., Özmen, H. & Ayas, A. (2004). Some concepts misconceptions encountered in chemistry: a research on acid and base. *Educational Sciences: Theory and Practice,* 4(1), 77-80.

Department of Education (2003) *National Curriculum Statement Grades 10-12 (General) Physical Sciences.* Pretoria, South Africa

Dhindsa, H. S. (2002). Preservice teachers' conceptions of pH. *Australian Journal of Education in Chemistry,* 60, 19-24.

diSessa, A. A. (1998). Knowledge in Pieces. In G. Forman & P. B. Puffall (Eds) *Constructivism in the Computer Age,* pp 49-70. Lawrence Earlbaum, Hillsdale.

Domin, D. S. (1996). Comment on "Concept mapping and representational systems". *Journal of Research in Science Teaching*, 33(8), 935-937.

Drechsler, M. & Schmidt, H.-J. (2005a). Textbooks' and teachers' understanding of acid-base models used in chemistry teaching. *Chemistry Education Research and Practice*, 6(1), 19-35. http://www.rsc.org/images/p2_drechsler_tcm18-31134.pdf [Retrieved 31st March 2009]

Drechsler, M. & Schmidt, H.-J. (2005b). Upper secondary school students' understanding of models used in chemistry to define acids and bases. *Science Education International,* 16(1), 35-53.

Drechsler, M. & van Driel, J. (in press) Teachers' knowledge and beliefs about teaching of acids and bases in Swedish upper secondary schools. Submitted to *International Journal of Science Education*.

Drechsler, M. (2007). *Models in chemistry education: a study of teaching and learning acids and bases in Swedish upper secondary schools.* Doctoral thesis, Faculty of Technology and Science, Karlstad University, Karlstad

Driver, R. & Easley, J. (1978). Pupils and Paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education*, 5, 61-84.

Driver, R. (1995). Constructivist approaches to science teaching. In L.P. Steffe, & J. Gale (Eds) *Constructivism in education* (pp 385-400). Lawrence Erlbaum, Hillsdale

Driver, R., Guesne, E. & Tiberghien, A. (1985) (Eds) *Children's Ideas in Science*. Open University Press, Milton Keynes.

Duit, R. & Treagust, D. (1995). Students' conceptions and constructivist teaching approaches. In B. J. Fraser & Walberg, H. J. (Eds) pp 46-69 *Improving Science Education* University of Chicago Press, Chicago

Erduran, S. (1996). Analysis of physical science textbooks for conceptual frameworks on acids, bases and neutralization: implications for student understanding. *Annual Meeting of the American Educational Research Association.* New York. ERIC document ED 395 791

Erduran, S. (2003). Examining the mismatch between pupil and teacher knowledge in acid-base chemistry. *School Science Review*, 84(308), 81-86.

Erickson, G. (2000) Research programmes and the students science learning literature. In R. Millar, J. Leach & J. Osborne (Eds) *Improving Science Education: the contribution of research* pp 271-292, Open University Press, Buckingham

Erickson, G. L. (1979). Children's conception of heat and temperature. *Science Education*, 63, 221-230.

Evans, D. A. (2006) Fear of all snakes, spiders, ...and chemicals. *Chemistry International,* July-August, 12-15. From http://old.iupac.org/publications/ci/2006/2804/3_Evans.html [Retrieved on 8th June 2007]

Evans, E. W. & Lewis, Rh. (1998). The teaching of basic chemistry to university foundation students. *University Chemistry Education,* 2(2), 55-57 http://www.rsc.org/images/Vol_2_No2_tcm18-7035.pdf [Retrieved 30 March, 2009]

Eybe, H. & Schmidt, H.-J. (2001). Quality criteria and exemplary papers in chemistry education research. *International Journal of Science Education*, 23(2), 209-225.

Finley, F. N. & Stewart, J. (1982) Representing Substantive Structures. *Science Education*, 66(4), 593-611.

Finley, F. N., Stewart, J. & Yarroch, W. L. (1982). Teachers' perceptions of important and difficult science content. *Science Education*, 66, 531-538 .

Frappaolo, C. (2006). *Knowledge management*. Capstone, Chichester.

Furió, C., Azonca, R. & Guisasola, J. (2002). The Learning and teaching of the concepts 'amount of substance' and 'mole': A review of the literature. *Chemistry Education: Research and Practice* 3(3) 277-292 http://www.uoi.gr/cerp/2002_October/pdf/02Furio.pdf [Retrieved 7th June 2006]

Furió-Más, C., Calatayud, M. L., Guisasola, J. & Furió-Gomez, C. (2005). How are the concepts and theories of acid-base reactions presented? Chemistry in textbooks and as presented by teachers. *International Journal of Science Education*, 27(11), 1337-1358.

Furió-Más, C., Calatayud, M.-L. & Bárcenas, S. L. (2007). Surveying students' conceptual and procedural knowledge of acid-base behaviour. *Journal of Chemical Education*, 84(10), 1717-1724. Supplemental material from http://jchemed.chem.wisc.edu/Journal/Issues/2007/Oct/ [Retrieved 8th February 2008]

Gabel, D. L., Samuel, K. V., Hunn, D. J. (1987). Understanding the particulate nature of matter. *Journal of Chemical Education*, 64, 695-697.

Gabel, D. (1989). Let us go back to nature study. *Journal of Chemical Education*, 66(9), 727-29.

Gabel, D. (1993). Use of the particulate nature of matter in developing conceptual understanding. *Journal of Chemical Education*, 70(3), 193-194.

Gabel, D. (1999). Improving Teaching and learning through chemistry education research, a look to the future. *Journal of Chemical Education*, 76(4), 548-554.

Gabel, D. L. & Bunce, D. M. (1994) Research on problem solving in chemistry In D. L. Gabel (Ed) *Handbook of Research on science teaching and learning*. Macmillan, New York pp301-326.

Galili, I. & Lehavi, Y. (2006). Definitions of physical concepts: a study of teachers' knowledge and views. *International Journal of Science Education*,28(14), 521-541.

Garnett, P. J., Garnett, P. J. & Hackling, M. W. (1995). Student's Alternative Conceptions in Chemistry: A Review of Research and Implications for Teaching and Learning. *Studies in Science Education*, 25, 69-95.

Gilbert, J. K., Boulter, C. J & Elmer, R. (2000). Positioning Models in Science Education. In J. K. Gilbert & C. J. Boulter (Eds) *Developing models in science education* (pp3-18). Kluwer Academic Press, Dordrecht.

Gilbert, J. K., De Jong, O., Justi, R., Treagust, D. F. & Van Driel, J. H. (2002a). Research and development for the future of chemical education. The current balance of types of research into chemical education. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust & J. H. van Driel (Eds) *Chemical Education: Towards Research-Based Practice*, pp 391-408, Kluwer, Dordrecht.

Glynn, S. M., Yeany, R. H. & Britton, B. K. (1991). A constructive view of learning science in S.M. Glynn, R. H. Yeany & B. K. Britton (Eds) *The psychology of learning science* pp3-19. Lawrence Erlbaum, Hillsdale.

Glynn, S., Duit, R. (1995). Learning Science Meaningfully: Constructing Conceptual Models. In S. M. Glynn & R. Duit (Eds) *learning science in the schools: Research reforming practice*. pp 3-33 Lawrence Erlbaum, Mahwah.

Goodstein, M. P. & Howe, A. C. (1978). Application of Piagetian theory to introductory chemistry instruction. *Journal of Chemical Education*, 55(3), 171-173

Grayson, D. J. (1996) A holistic approach to preparing disadvantaged students to succeed at tertiary science studies. Part I: Design of the Science Foundation Programme (SFP). *International Journal of Science Education*, 18(8), 993-1013.

Grayson, D. J., Anderson, T. R., & Crossley, L. G. (2001). A four-level framework for identifying and classifying student conceptual and reasoning difficulties. *International Journal of Science Education*, 23(6), 611-622.

Hall, N. F. (1930). Modern conceptions of acids and bases. *Journal of Chemical Education*, 7, 782-793.

Halakova, Z. & Proksa, M. (2007). Two kinds of conceptual problems in chemistry teaching. *Journal of Chemical Education*, 84(1). 172-174.

Hammer, D. (2000). Student resources for learning introductory physics. Physics Education Research, *American Journal of Physics* Supplement 68(7), S52-S59.

Hand, B. M. (1989). Students' understanding of acids and bases: A two year study. *Research in Science Education*, 19, 133-144.

Hand, B. M. & Treagust, D. F. (1988). Application of conceptual conflict strategy to enhancing student learning of acids and bases. *Research in Science Education*, 18, 53-63.

Hawkes, S. J. (1992). Arrhenius confuses students. *Journal of Chemical Education*, 69(7), 542-543.

Hawkes, S. J. (1994). Teaching the truth about pH. *Journal of Chemical Education*, 71(9), 747-749.

Hawkes, S. J. (1996a). Salts are mostly NOT ionized. *Journal of Chemical Education*, 73(5), 421-23.

Hawkes, S. J. (1996b). Buffer calculations deceive and obscure. *The Chemical Educator*, 1(6), 1-8

Herron J. D. (1975). Piaget for chemists. Explaining what "good" students cannot understand. J*ournal of Chemical Education*, 52(2), 146-150.

Herron, J. D. (1996). *The Chemistry Classroom.* American Chemical Society, Washington.

Herron, J. D. (1979). Hey, watch your language! *Journal of Chemical Education*, 56(5), 330-331.

Hestenes, D., Wells, M. & Swackhamer, G. (1992). Force Concept Inventory. *The Physics Teacher*, 30(3), 141-158.

Hewson, M. G. & Hewson, P. J. (1983). Effect of Instruction using students' prior knowledge and conceptual change strategies on science learning. *Journal of Research in Science Teaching,* 20, 731-743.

Hewson, M.G.A'B. (1985) The role of intellectual environment in the origin of conceptions: an exploratory study. In L. H. T. West,. & A. L. Pines (Eds) *Cognitive Structure and Conceptual Change* pp153-161. Academic Press, Orlando.

Hodson, D. (1992). In Search of Meaningful relationship: an exploration of some issues relating to integration in science and science education. *International Journal of Science Education,* 14(5), 541-562.

Hoffmann, R. & Laszlo, R. (1991). Representation in chemistry. *Angewandte Chemie,* 30(1), 1-16.

Horton, Chris (2001) *Student preconceptions and Misconceptions in chemistry: Integrated physics and chemistry modelling workshop.* Arizona State University, June 2001 Version 1.35 from http://www.daisley.net/hellevator/misconceptions/misconceptions.pdf [Retrieved 4th May 2006]

Howitt, S., Anderson, T., Costa, M., Hamilton, S. & Wright, T. (2008). A concept inventory for molecular life sciences: how will it help your teaching practice? *Australian Biochemist,* 39(3), 14-17).

Huddle, P. A. & Pillay, A. E. (1996). An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African University. *Journal of Research in Science Teaching,* 33, 65-77.

Independent Examination Board (1997) *Senior Certificate Examination Resource Material for Physical Science.* Johannesburg, South Africa

Jenkins, E. W. (2000). Research in Science Education : Time for a Health Check? *Studies in Science Education,* 35, 1-26.

Jensen, W. B. (2004). The Symbol for pH. *Journal of Chemical Education,* 81-21.

Johansson, B., Martin, F. & Svenson, L. (1985). An Approach to Describe Learning. In L.H.T. West, & A.L. Pines (Eds) *Cognitive Structure and Conceptual Change*. Academic Press, Orlando

Johnson, C. C., Kable, J. B. & Fargo, J. D. (2007). Effective teaching results in increased science achievement for all students. *Science Education*, 91(2), 371-383.

Johnson, P. (2002). Children's understanding of substances, Part 2: explaining chemical change. *International Journal of Science Education*, 24(10), 1037-1054.

Johnson, P. & Gott, R. (1996). Constructivism and evidence from children's ideas. *Science Education*, 80(5), 561-577, Johnson-Laird, R. N. (1983). *Mental models: towards a cognitive science of language and conscientiousness.* Cambridge University Press, Cambridge

Johnstone, A. H. (1982). Macro and microchemistry. *School Science Review*, 64(227), 377-379.

Johnstone, A. H. (1991). Why is science difficult to learn? Things are seldom what they seem. *Journal of Computer Assisted Learning*, 7, 75-83.

Johnstone, A. H. (1993). The development of chemistry teaching, A changing response to changing demand. *Journal of Chemical Education*, 70(9), 701-705.

Johnstone, A. H. (1999). The nature of chemistry. *Education in Chemistry*, 36(2), 45-47.

Johnstone, A. H. (2000). Chemical education research: Where from here? *University Chemistry Education* 4(1) 34-38 http://www.rsc.org/images/Vol_4_No1_tcm18-7038.pdf [Retrieved 30th March, 2009]

Johnstone, A. H. (2002). Teaching of Chemistry – Logical or psychological? *Chemistry Education: Research and Practice in Europe,* 1(1), 9-15.http://www.uoi.gr/cerp/2000_January/pdf/056johnstonef.pdf [Retrieved 6th March 2009]

Justi, R. S. (2000). Teaching with historical models. In J. K. Gilbert, & C. J. Boulter (Eds) *Developing models in science education,* pp 209-226. Kluwer Academic Press, Dordrecht.

Justi, R. S. & Gilbert, J. K. (2002a). Modelling teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education*, 24(4), 369-387.

Justi, R. & Gilbert, J. (2002b). Models and Modelling in Chemical Education. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. van Driel (Eds) C*hemical education: towards research based practice,* pp 47-68, Kluwer Academic Publishers, Dordrecht.

Justi, R. S. & Gilbert, J. K. A (1999). A cause of ahistorical teaching: Use of hybrid models. *Science Education*, 83, 163-177.

Kellogg, R. T. (2003). *Cognitive Psychology (2nd ed)* Sage Publications, Thousand Oaks.

Kerlinger, F. D. (1986). *Foundations of behavioral research (3rd ed)* Holt, Rinehart and Winston,: New York.

Kind, V. (2004). *Beyond Appearances: Students' misconceptions about basic chemical ideas (2nd ed)* http://www.magma.ca/~dougdela/3dfiles/royal.pdf [Retrieved 9th March, 2009]

Kobe, K. A.. & Markov, T. S. (1941). The preparation of ammonium hydroxide for laboratory use. *Journal of Chemical Education*, 18, 29.

Kolb, D. (1978). Chemical principles revisited: acids and bases. *Journal of Chemical Education*, 55(7), 459-64.

Kousathana, M. Demerouti, M & Tsaparlis, G. (2005). Instructional Misconceptions in Acid-Base equilibria: An analysis from a history and philosophy of science perspective. *Science & Education* 14, 173-193.

Kozma, R. B. & Russell, J. (1997). Multimedia and understanding: Expert to novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching,* 34(9), 949-65.

Krnel, D., Watson, R. & Glazer, S. A. (1998). Survey of research related to the development of the concept of 'matter'. *International Journal of Science Education*, 20(3), 257-289.

Kruse, R. A. & Roehrig, G. H. (2005). A comparison study: assessing teachers' conceptions with the chemistry concepts inventory. *Journal of Chemical Education*, 82(8), 1246-1250.

Kuhn, T.S. (1970). *The Structure of Scientific Revolutions. (2nd ed)* University of Chicago Press, Chicago

Laing, M. & Laing, M. (1988). There is no such thing as NH_4OH. *Spectrum*, 26(4), 11.

Laing, M. (1999). The four-fold way. *Education in Chemistry,* 36(1), 11-13.

Lakatos, I. (1978) The methodology of scientific research programmes. In J. Worrall, G. Currie (Eds) *Philosophical papers Vol I.* Cambridge University Press, Cambridge

Lambert, J. (2005) Students' conceptual understanding of science after participating in a high school marine science course. *Journal of Geoscience Education*, 53(5), 531-539 http://nagt.org/files/nagt/jge/abstracts/lambert-v53n5.pdf [Retrieved 11th February 2007]

Land, L., Cousin, G., Meyer, J. H. F. & Davies, P. (2006) Conclusion: Implications of threshold concepts for course design and evaluation. In J. H. F. Meyer & R. Land (Eds) *Overcoming barriers to students understanding: threshold concepts and troublesome knowledge*. pp 195-206, London, Routledge.

Larkin, J.H. & Reif, F. (1976). Analysis and teaching of a general skill for studying scientific text. *Journal of Educational Psychology,* 68(4), 431-440.

Laugksch, R. (2002) Analysis of South African postgraduate degrees in science education: 1930-2000 In C. Malcolm & C. Lubisi (Eds) *Proceedings of the 10th Annual Conference of the South African Association for Research in Mathematics, Science and Technology Education.* pp III-198-204, University of Natal, Durban.

Lawn, R. (2003). *Practical laboratory skills training guides: measurement of pH.* Royal Society of Chemistry

Lawson, A. E. & Thompson, L.D. (1988) *Formal reasoning ability and misconceptions concerning genetics and natural selection. Journal of Research in Science Teaching,* 25(9), 733-746.

Lawson, A. E., Baker, W. P., DiDonato, L., Verdi, M. P. & Johnson, M. A. (1993). The role of hypothetic-deductive reasoning and physical analogues of molecular interactions in conceptual change. *Journal of Research in Science Teaching,* 30(9), 1073-1085.

Lee, E. & Luft, J. A. (2008) Experienced secondary science teachers' representation of pedagogical content knowledge. *International Journal of Science Education*, 30(10), 1343-1363.

Lee, K. L. (1999). A comparison of University Lecturers' and Pre-service Teachers' understanding of a chemical reaction at the particulate level. *Journal of Chemical Education*, 76(7), 1008-1012.

Lewis, E. L. & Linn, M. C. (1994). Heat energy and temperature concepts of adolescents, adults and experts: Implications for curricular improvements. *Journal of Research in Science Teaching,* 31(6), 657-677.

Lide, D. R. (Ed) (2002). *CRC Handbook of Chemistry and Physics (83rd ed)* CRC Press, London.

Lin, J.-W. & Chiu, M.-H. (2007). Exploring the characteristics and diverse sources of students' mental models in acids and bases. *International Journal of Science Education*, 29(6), 771-803.

Lin, J.-W., Chiu, M.-H. & Liang, J.-C. (2004) Exploring mental models and causes of students' misconceptions in acids and bases. http://science.gise.ntnu.edu.tw/profile/workshop/NARST2004full%20text0213acid%20and%20base.pdf [Retrieved 12th June 2007]

Lincoln, Y. S. & Guba, E. G. (1985). *Naturalistic Inquiry.* Sage, Newbury Park.

Linke, R. D. & Venz, M. L. (1979). Misconceptions in physical science among non-science background students: II. *Research in Science Education*, 9, 103-109.

Liu, X. (2001). Synthesizing research on student conceptions in science. *International Journal of Science Education*, 23(1), 55-81.

Loeffler, P. A. (1989). Fundamental concepts in teaching of chemistry Part 1. The two worlds of the chemist make nomenclature manageable. *Journal of Chemical Education*, 66(11), 928-930.

Longden, K., Black, P. & Solomon, J. (1991). Children's' interpretation of dissolving. *International Journal of Science Education,* 13(1) 59-68.

Lowry, T. M. (1923). The uniqueness of hydrogen. *Chemistry and Industry*, 42, 43-47

Lowry, T. M. (1924). The electronic theory of valency: Part IV. The origin of acidity. *Transactions of the Faraday Society*, 20(18) 13-17.

Lubben, F., Bennett, J., Campbell, B., & Hogarth, S. (2005) A systematic review of the role of small-group discussions in science teaching In C. Kasanda, L. Muhammed, S. Akpo & Ngolo (Eds) *Proceedings of the Southern African Association of Research in Mathematics, Science and technology Education Conference (SAARMSTE,)* Windhoek.

Lythcott, J. (1985). "Aristotelian" was given as the answer, but what was the question? *American Journal of Physics*, 53, 428-432.

Marais, P. & Jordaan, F. (2000). Are we taking symbolic language for granted? *Journal of Chemical Education*, 77(10), 1355-1357.

Marín, N., Gómez, E. J. & Benarroch, A. (2004). How can we identify replies that accurately reflect students' knowledge? A methodological proposal. *International Journal of Science Education*, 26(4), 425-445.

Matthews, M. (1994). Discontent with constructivism. *Studies in Science Education,* 24, 165-72.

Maxwell, J. A. (2005). *Qualitative research design: an interactive approach.* Sage, Thousand Oaks.

Mazur, E. (1997). *Peer instruction: A user's manual.* Prentice-Hall, Upper Saddle River.

Mbewe, B. (2000). Quaternary structure as defined by whom? *Biochemistry and Molecular Biology Education*, 28(5), 240-241.

McMillan, J. H. & Schumacher, S. (1993). *Research in education: A conceptual introduction (3rd ed).* Harper Collins College Publishers, New York.

McNaught, A. D. & Wilkinson, A. (1997) *IUPAC. Compendium of chemical terminology, 2nd ed.* (the "Gold book") http://old.iupac.org/publications/compendium/index.html [Retrieved 2nd December 2007]

Meyer, J. H. F. & Land, R. (2006). Threshold concepts and troublesome knowledge, an introduction. In J. H. F. Meyer & R. Land (Eds) *Overcoming barriers to students understanding: threshold concepts and troublesome knowledge*. pp 3-18 London, Routledge

Millar, R. (1989). Constructive criticisms. *International Journal of Science Education,* 11, 587-596.

Mintzes, J. J. & Novak, J. D. (2000). Assessing science understanding: The epistemological vee diagram. In J. J. Mintzes J. H. Wandersee & J. D. Novak (Eds) A*ssessing science understanding.* pp 41-71 Academic Press, San Diego.

Mintzes, J. J & Wandersee, J. H. (1998). Research in Science Teaching and Learning: A human constructivist view. In J. J. Mintzes, J. H. Wandersee & J. D. Novak (Eds) *Teaching science for understanding: a human constructivist view* pp59-92 Academic Press, San Diego.

Moji, N. C. (1998). *Investigation of conceptual and language difficulties affecting the understanding of several mechanics concepts among some African teachers and students.* PhD thesis, University of Natal.

Moran, M. J. (2006). Factors that influence relative acid strength in water: a simple model. *Journal of Chemical Education,* 83(5), 800-803.

Morgil, I., Yavaz, S., Osakay, Ö., Özyal & Arda, S. (2005). Traditional and computer-assisted learning in teaching acids and bases. *Chemistry Education Research and Practice*, 6(1), 52-63. http://www.rsc.org/images/p4_Morgil_tcm18-31136.pdf [Retrieved 31st October 2005]

Morrison, R. T. & Boyd, R. N. (1966). *Organic Chemistry (2nd ed).* Allyn & Bacon, Boston.

Morse, D. & Jutras, F. (2008). Implementing concept-based learning in a large undergraduate classroom. *CBE Life Sciences Education*, 7, 243-353.

Mulford, D. R. & Robinson, W. R. (2002). An inventory for alternative conceptions among first-semester general chemistry students. *Journal of Chemical Education.* 79(6), 739-744.

Muthukrishna, N., Carnine, D., Grossen. & Miller, S. (1993) Children' alternative frameworks: should they be directly addresses by science instruction? *Journal of Research in Science Teaching,* 30, 233-248.

Nakhleh, M. B. (1994). Students' models of matter in the context of acid-base chemistry. *Journal of Chemical Education*, 71(6), 495.

Nakhleh, M. B. & Krajcik, J. S. A. (1993). Protocol analysis of the influence of technology on Students' actions, verbal commentary, and thought processes during the performance of acid base titrations. *Journal of Research in Science Teaching*, 30(9), 1149-1168.

Nakhleh, M. & Krajcik, J. S. (1994). Influence of levels of information as presented by different technologies on student understanding of acid-base and pH concepts. *Journal of Research in Science Teaching,* 31, 1077-1096.

Nakhleh, M. B. & Krajcik, J. S. (1996). Reply to Daniel S. Domin's comment on concept mapping and representational systems. *Journal of Research in Science Teaching,* 33(8), 937-938.

Nelson, P. G. (2002) Teaching chemistry progressively: from substances to atoms and molecules, to electrons and nuclei. *Chemistry Education: Research and Practice in Europe,* 3(2), 215-228. http://www.uoi.gr/cerp/2002_May/pdf/11Nelson.pdf [Retrieved 6th May 2008]

Nelson, P. G. (2003). Basic chemical concepts. *Chemistry Education: Research and Practice in Europe,* 4(1), 19-24 http://www.uoi.gr/cerp/2003_February/04.html [Retrieved 6th May 2008]

Nelson, P. G. (2006), Definition of an element. *Chemistry Education: Research and Practice in Europe,* 7(4), pp 288-289. http://www.rsc.org [Retrieved 10th May 2006].

Nicoll, G. (2003) A qualitative investigation of undergraduate chemistry students' macroscopic interpretations of the submicroscopic structure of molecules. *Journal of Chemical Education*, 80(2), 205-213.

Novak, J. D. (1985). Meta-learning and meta knowledge strategies to help students learn how to learn. In L. H. T. West, & A.L. Pines (Eds) *Cognitive Structure and Conceptual Change* pp189-209. Academic Press, Orlando.

Novak, J. D. (1996). Concept mapping: a tool for improving science teaching and learning In D. F. Treagust, R. Duit & B. J. Fraser (Eds) *Improving Teaching and Learning in Science and Mathematics,* pp 32-43. Teachers College Press, Columbia University, New York.

Novak, J. D. (2002). Meaningful Learning: The essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Science Education,* 86, 548-571.

Novak, J. D. & Gowan, D. B. (1984). *Learning How to Learn.* Cambridge University Press, Cambridge

Novick, S. & Nussbaum, J. (1978). Junior High School pupils' understanding of the particulate nature of matter. *Science Education* 62, 273-281.

Nussbaum, J. (1979). Children's conception of the earth as a cosmic body: A cross-age study. *Science Education,* 63(1), 83-93.

Nussbaum, J. (1998). History and philosophy of science and the preparation for constructivist teaching: the case of particle theory. In J. J. Mintzes,, J. H. Wandersee & J. Novak (Eds). *Teaching science for understanding: A human constructivist view* (pp 165-194). San Diego, Academic Press.

Ogunniyi, M. & Mikalsen, O. (2004). Ideas and process skills used by South African and Norwegian student to perform cognitive tasks on acids, bases and magnetism. *African Journal of Research in Science, Mathematics and Technology Education*, 8(2), 151-164.

Orgill, M. K. & Sutherland, A. (2008). Undergraduate chemistry students' perceptions of and misconceptions about buffers and buffer problems. *Chemistry Education: Research and Practice*, 9,131-143

Osborne, J. F. (1996). Beyond Constructivism. *Science Education*, 80(1), 53-82.

Osborne, R. J. & Cosgrove, M. M. (1983). Children's conceptions of the changes of state of water. *Journal of Research in Science Teaching*, 20(9), 825-838.

Ouertatani, L., Dumon, A., Trabelsi, A. & Soudani, M. (2007). Acids and bases: The appropriation of the Arrhenius model by Tunisian Grade 10 students. *International Journal of Science and Mathematics Education*, 5, 483-506.

Oversby, J. (2000a). Models of Explanation in Chemistry: The case of acidity. In J. K. Gilbert & C. Boulter (Eds) *Developing models in science education*, pp 227-232. Kluwer Academic Press, Dordrecht.

Oversby, J. (2000b). Is it a weak acid or a weakly acid solution? *School Science Review*, 81(297), 89-91

Özmen, H. (2004) Some student misconceptions in chemistry: A literature review of chemical bonding *Journal of Science Education and Technology* 13 (2) 147-159

Palmer, D. (2005). A motivational view of constructivist- informed teaching. *International Journal of Science Education*, 27 (15), 1853-1881.

Park, E. J. & Light, G. (2009). Identifying atomic structure as a threshold concept: student mental models and troublesomeness. *International Journal of Science Education, 3192 233-258.*

Perkins, D. (1999). The many faces of constructivism. *Educational Leadership*, 57(3), 6-11.

Perkins, D. (2006a). Constructivism and troublesome knowledge. In J. H. F. Meyer & R. Land (Eds) *Overcoming barriers to students understanding: threshold concepts and troublesome knowledge*. pp 33-47 London, Routledge.

Perkins, D. (2006b) Threshold concepts: How can we recognise them? In J. H. F. Meyer & R. Land (Eds) *Overcoming barriers to students understanding: threshold concepts and troublesome knowledge*. pp 70-84 London, Routledge.

Pinarbasi, T. (2007). Turkish undergraduate students' misconceptions on acids and bases. *Journal of Baltic Science Education* 6(1) 23-34. http://web.ebscohost.com/ehost/pdf?vid=8&hid=105&sid=71c0dd41-75cc-48d3-80a2-4a5f46b77d23%40sessionmgr102 [Retrieved 11th December 2007]

Pines, A. L. (1985). Towards taxonomy of conceptual relations and the implications for the evaluation of cognitive structure. In L. H. T. West, & A. L. Pines (Eds) *Cognitive Structure and Conceptual Change*. Pp 106-116 Academic Press, Orlando.

Pines, A. L. & West, L. H. T. (1986). Conceptual understanding and science learning: An interpretation of research within a sources-of- knowledge framework. *Science Education*, 70(5), 583-604.

Pinto, R. C. & Blair, J. A. (1993) *Reasoning: A Practical Guide*. Prentice Hall, Englewood Cliffs.

Potgieter, M., Harding, H. & Egelbrecht, J. (2008) Transfer of Algebraic and graphical thinking between mathematics and chemistry. *Journal of Research in Science Teaching*, 45(2), 197-218.

Potgieter, M., Rogan, J. M. & Howie, S. (2005). Chemical concepts inventory for Grade 12 learners and UP foundation year students. *African Journal of Research in Science, Mathematics and Technology Education*, 9(2), 121-134.

Pushkin, D.B. (1996). A comment on the need to use appropriate scientific terminology in conception studies. *Journal of Research in Science Teaching*, 33(2), 223-224.

Pyramid Film & Video (1988). *A private universe. An insightful lesson on how we learn* [Flier]. Santa Monica, CA (cited by Wandersee *et al.*, 1994)

Ratcliffe, M. (2002). What's difficult about A-level chemistry? *Education in Chemistry*, 76-77, 80.

Rayner-Canham, G. (1994). Concepts of acids and bases. *Journal of College Science Teaching*, 23(4), 246-247.

Rhodes, S. (2006). Getting back to basics (& acidics).*The American Biology Teacher*, 68(10), 24-27.

Rivet, A. E. & Krajcik, J. S. (2008) Contextualizing instruction: Leveraging students' prior knowledge and experiences to foster understanding of middle school science. *Journal of Research in Science Teaching*, 45(1), 79-100.

Rollnick, M., Bennett, J., Rhemtula, M., Dharsey, N. & Ndlovu, T. (2008). The place of subject matter knowledge in pedagogical content knowledge: a case study of South African teachers teaching the amount of substance and chemical equilibrium. *International Journal of Science Education*, 30(10), 1365-1387.

Ross, B. & Munby, H. (1991). Concept mapping and misconceptions: a study of high-school students' understanding of acids and bases. *International Journal of Science Education*, 13(1), 11-23.

Sacks, L. J. (2007). Concerning Lewis Acid-Base Theory for Proton Transfer. *Journal of Chemical Education*, 84(9), 1415-1416.

Salloum, S. L. & BouJaoude, S. (2008). Careful! It is H_2O? Teachers' conceptions of chemicals. *International Journal of Science Education*, 30(1), 33-64.

Sanders, M. (1993). A framework for improving the quality of quantitative research in science education. Paper presented at the Annual Conference of the National Association for Research in Science Teaching, 15-19 April 1993, Atlanta, Georgia, USA.

Sanger, M. J. & Greenbowe, T. J. (1999). An analysis of college chemistry textbooks as source of misconceptions and errors in electrochemistry. *Journal of Chemical Education*, 76(6), 853-860.

Sawyer, D. T. (2005) Conceptual Considerations in Molecular Science. *Journal of Chemical Education*, 82(7), 985-987.

Schmidt, H.-J. (1991). A label as a hidden persuader: chemists neutralisation concept. *International Journal of Science Education*, 13(4), 459-471.

Schmidt, H.-J. (1995). Applying the concept of conjugation to the Brønsted theory of acid – base reactions by senior high school students from Germany. *International Journal of Science Education*, 17 (6), 733-741.

Schmidt, H.-J. (1997). Student misconceptions – Looking for a pattern. *Science Education*, 81(2), 123-135.

Schmidt, H.-J. & Volke, D. (2003). Shift of meaning and students' alternative concepts. *International Journal of Science Education*, 25(11), 1409-1424.

Schönborn, K. J. & Anderson, T. R. (2008a). Bridging the educational research-teaching gap: Conceptual understanding, Part 1: The multifaceted nature of expert knowledge. *Biochemistry and Molecular Biology Education*, 36(4), 309-315.

Schönborn, K. J. & Anderson, T. R. (2008b). Bridging the educational research-teaching gap: Conceptual understanding, Part 2: Assessing and developing student knowledge. *Biochemistry and Molecular Biology Education*, 36(5), 372-379.

Schroeder, C. M., Scott, T. P.; Tolson, H.; Huang, T.-Y. & Lee, Y.-H. (2007) A meta-analysis of national research: effects of teaching strategies on student achievement in science in the United States. *Journal of Research in Science Teaching, 44(10), 1436-1460.*

Selley, N. J. (2000) Students' spontaneous use of a particulate model for dissolution. *Research in Science Education*, 30(4), 389-402.

Shaffer, A. A. (2006). Let us give Lewis acid-base theory the priority it deserves. *Journal of Chemical Education*, 83(12), 1746-1749.

Sheppard, K. (2006). High-school students' understanding of titrations and related acid-base phenomena. *Chemistry Education Research and Practice*, 7(1), 32-45 http://www.rsc.org/images/Sheppardpaper_tcm18-46455.pdf [Retrieved .20th December, 2008]

Shulman, L. S. (1986). Those who understand: knowledge growth in teaching. *Educational Researcher*, 15(2), 4-14.

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review,* 57(1), 1-22.

Skoog, D. A., West, D. M. & Holler, F. J. (1996) *Analytical chemistry (7th ed)* Orlando, Sanders College Publishing.

Smith, B. D. & Jacobs, D. C. (2003). TextRev: A Window into How General and Organic Chemistry Students Use Textbook Resources. *Journal of Chemical Education* , 80(1), 99-102.

Smith, E. E. & Medin, D. L. (1981). *Categories and Concepts*. Harvard University Press, Cambridge.

Smith, E. L. (1991). A conceptual change model of learning science. In S. M. Glynn, R. H. Yeany & B. K. Britton (Eds) *The Psychology Of Learning Science,* pp 43-63, Lawrence Erlbaum, Hillsdale.

Smith, J. P., diSessa, A. A. & Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences,* 3(2), 115-163.

Smith, K. & Metz, P. (1996). Evaluating student understanding of solution chemistry through microscopic representations. *Journal of Chemical Education,* 73, 233-235.

Solomon, J. (1993a). The social construction of children's scientific knowledge, In P. J. Black & A. M. Lucas (Eds) *Children's informal ideas in science,* pp 85-101,Routledge, London.

Solomon, J. (1993b). Four Frames for a field. In P. J. Black & A. M. Lucas (Eds) *Children's informal ideas in science,* pp1-19, Routledge, London.

Solomon, J. (1994). The rise & fall of constructivism. *Studies in Science Education*, 23, 1-19.

Solomonidou, C. & Stravrido, H. (2000). From inert object to chemical substance: Student's initial conceptions and conceptual development during an introductory experimental chemistry sequence. *Science Education,* 84, 382-400.

Sörenson, S. P. L. (1909). Enzyme Studies II. The Measurement and Meaning of hydrogen on Concentration in Enzymatic Processes. *Biochemische Zeitchrift* 21, 131-200 http://chemteam.info/Chem-History/Sorenson-article.html [Retrieved 19th March 2009]

Stains, M. & Talanquer, V. (2007). A_2: Element or Compound? *Journal of Chemical Education*, 84(5), 880-883.

Stains, M. & Talanquer, V. (2008). Classification of chemical reactions: stages of expertise. *Journal of Research in Science Teaching*, 45(7), 771-793.

Stavridou, H. & Solomonidou, C. (1998) Conceptual reorganization and the construction of the chemical reaction concept during secondary education. *International Journal of Science Education*, 20(2), 205-221.

Stavy, R. & Tirosh, D. (2000) *How Students (mis)understand science and mathematics: intuitive rules.* Teachers' College Press, Columbia University, New York.

Strike, K. A. & Posner, G. J. (1982). Conceptual change and science teaching. *European Journal of Science Education,* 4(3), 231-240.

Sumfleth, E. (1987). Über den Zusammerhang zwischen Schullenistung und Gedächtnis-stuktur-Eine Untersuchung zum Thema Säure-Base – Reaktionen. *Natuurwissen-schaften im Unterricht.* 35, 29-35 (cited by Schmidt, 1995; Demerouti *et al.,*2004)

Sutherland, S (1989). *Macmillan Dictionary of Psychology,* Macmillan Press, London.

Szabadváry F. (1964). Development of the pH Concept, A historical survey. *Journal of Chemical Education*, 41(2), 1964.

Taber, K. S. (2001a). Building the structural concepts of chemistry: some considerations from educational research *Chemistry Education Research and Practice*, 2(2), 123-158. http://www.uoi.gr/cerp/2001_May/pdf/09Taber.pdf [retrieved 20th March 2008]

Taber, K. S. (2001b). Shifting sands: a case study of conceptual development as competition between alternative conceptions. *International Journal of Science Education,* 23(7), 731-753.

Taber, K. (2001c). The campaign to stop molecules reacting. *Education in Chemistry,* 90(1), 28.

Taber, K. (2002) *Chemical Misconceptions – prevention, diagnosis and cure, Vol 1: Theoretical background.* Royal Society of Chemistry, London.

Taber, K. S. (2006) Beyond Constructivism: the progressive research programme into learning science. Studies in Science Education, 42, 125-184.

Talanquer, V. (2002). Minimising Misconceptions. *The Science Teacher,* American Science Teachers Association, 69 (8), 46-49.

Talanquer, V. (2006). Commonsense chemistry: a model for understanding students' alternative conceptions. *Journal of Chemical Education*, 83(5), 811- 816.

Talanquer, V. (2008). Students' predictions about sensory properties of chemical compounds: Additive versus emergent frameworks. *Science Education,* 92(1), 96-114.

Tan, K. C. D., Goh, N. K, Chia, L. S. & Treagust, D. F. (2002). Development and application of a two-tier multiple choice diagnostic instrument to assess high school students' understanding of inorganic chemistry qualitative analysis. *Journal of Research in Science Teaching*, 39(4), 283-301.

Tarr, R S and Norwell, D Y (1985) A unifying clinical basis for teaching acid-base balance in biochemistry. *Biochemical Education*, 13(1) 14-17)

Terry, R. (1993). An alternative conception: representing representations. In P. J. Black & A.M. Lucas (Eds) *Children's informal ideas in science.* pp 62-84, Routledge, London.

Thagard, P. (1996). *Mind: introduction to cognitive science.* MIT Press, Cambridge.

Toplis, R. (1998). Ideas about acids and alkalis. *School Science Review*, 80(291), 67-70.

Torgerson, C. (2003). *Systematic Reviews.* Continuum, London.

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education,*10(2), 159-169.

Treagust, D. F. (1995). Diagnostic Assessment of Students' Science Knowledge. In S. M. Glynn & R. Duit (Eds) *Learning Science in the Schools: research reforming practice.* pp 327-346, Lawrence Erlbaum, Mahwah.

Treagust, D. F. & Mamiala, T. L. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, 25(11), 1153-1368.

Treagust, D. F., Duit, R. & Fraser, B. J. (1996) *Improving Teaching and Learning in Science and Mathematics.* Teachers College Press, Columbia University, New York.

Trowbridge, J. E. & Wandersee, J. H. (1998) Theory-Driven Graphic organizers. In J. J. Mintzes, J. H. Wandersee, & J. D Novak (Eds) *Teaching Science for Understanding: a human constructivist view,* pp 95-131. Academic Press, San Diego.

Tsai, C.-C. & Wen, M. L. (2005). Research and trends in science education from 1998 to 2002: a content analysis of publication in selected journals. *International Journal of Science Education,* 27(1), 3-14.

Tullberg, A., Strömdahl, H. & Lybeck, L. (1994) Students' conception of 1 mol and educators' conception of how they teach 'the mole'. *International Journal of Science Education,* 16, 145-156. [Cited by Furió *et al.,* (2002).]

Tuttle, T. R. (1991). Ammonium hydroxide: What is its structure? *Journal of Chemical Education*, 68(6), 533.

Ünal, S., Çalik, M., Ayas, A & Coll, R.K (2006). A review of chemical bonding studies: needs, aims, methods of exploring students' conceptions, general knowledge claims and student alternative conceptions. *Research in Science & Technological Education,* 24(2), 141-172.

Van Driel, J. H., de Jong, O, Verloop, N. (2002). The development of preservice chemistry teachers' pedagogical content knowledge. *Science Education*, 86, 572-590.

van Lubeck, H. (1999). Why not replace pH and pOH by just one acidity grade, AG? *Journal of Chemical Education*, 76(7), 892-893.

Vidyapati, T. J. & Seetharamappa, J. (1995). Higher secondary school students' concepts of acids and bases. *School Science Review*. 77 (278), 82-84.

Viglietta, L. (1996). Science education journals: from theory to practice. *Science Education,* 80(4), 367-394.

Vogel, A. I. (1961). *A text-book of quantitative inorganic analysis including elementary instrumental analysis (3rd ed).* Longmans, London.

Vogelazang, M. J. (1987). Development of the concept 'chemical substance' – some thoughts and arguments. *International Journal of Science Education,* 9(5), 519-528.

von Glasersfeld, E. (1995a) *Radical Constructivism: A way of knowing and learning*. Falmer Press, London.

von Glasersfeld, E. (1995b) A constructivist approach to teaching. In L.P. Steffe, & J. Gale (Eds) *Constructivism in education,* pp3-15. Lawrence Erlbaum, Hillsdale.

Wallace, M. & Wray, A. (2006). *Critical Reading and Writing for Postgraduates*. Sage Publications, London.

Wandersee, J. H., Mintzes, J. J & Novak, J. D. (1994). Research on Alternative Conceptions in Science In D. L.. Gabel (Ed) *Handbook of research on science teaching and learning* pp177-210, Macmillan, New York.

Watters, D. J. & Watters, J. J. (2006). Student understanding of pH. *Biochemistry and Molecular Biology Education,* 34(4), 278-284.

West, L. H. T. & Pines, A. L. (1985) (Eds) *Cognitive Structure and Conceptual Change.* Academic Press, Orlando

White, R. & Gunstone, R. (1992). *Probing Understanding*. Falmer Press, London.

Wilkes, L. M. & Batts, J. E. (1996). Registered nurses' ideas of physical science concepts relevant to their clinical practice. *Research in Science Education,* 26(3), 327-340.

Wilson, J. M. (1998). Differences in knowledge networks about acids and bases of Year-12, Undergraduate and postgraduate chemistry students. *Research in Science Education,* 28(4), 429-446.

Yarroch, W. L. (1985) Student Understanding of Chemical Equation Balancing. *Journal of Research In Science Teaching,* 22(5), 449-459.

Ye, R. & Wells, R. R. (1998). Student concept changes in acids and bases. *Proceedings of the National Science Teacher Association National Convention, Las Vegas, Nevada.* ERIC document Ed 425 060.

Yezierski, E. J. & Birk, J. P. (2006). Misconceptions about the particle nature of matter: Using animations to close the gender gap. *Journal of Chemical Education*, 83(6), 954-960.

Yoke, J. (1989). Ammonium hydroxide does not exist. *Journal of Chemical Education*, 66(4), 310.

Young, J. A. (2003a). Ammonia, aqueous. *Journal of Chemical Education*, 80(1), 24.

Young, J.A. (2003b). Citric acid. *Journal of Chemical Education*, 80(5), 480.

Zoller, U. (1996). The use of examinations for revealing and distinguishing between students' misconceptions, misunderstandings and no conceptions in college chemistry. *Research in Science Education*, 26(3), 317-326.

APPENDIX 1 LIST OF REPORTS USED IN CRITICAL ANALYSIS

Botton, C. (1995) Collaborative concept mapping and formative assessment key stage 3: Understandings of acids and bases. *School Science Review,* 77(279), 124-130

Bradley, J. D. & Mosimege, M. D. (1998). Misconceptions in acids and bases: a comparative study of student teachers with different chemistry backgrounds. *South African Journal of Chemistry,* 51(3), 137-145.

Camacho, M. & Good, R. (1987) Problem solving and chemical equilibrium: successful versus unsuccessful performance. *Journal of Research in Science Teaching,* 26(3), 251-272

Chiu, M.-H. (2005) A national survey of students' conceptions in chemistry in Taiwan. *Chemical Education International,* 6 (1), 2005 from http://old.iupac.org/publications/cei/vol6/07_Chiu.pdf [Retrieved 9th June 2008]

Chiu, M.-H. (2007) A national survey of students' conceptions in chemistry in Taiwan. *International Journal of Science Education,* 29(4), 421-452

Cros, D., Chastrette, M., & Fayol, M. (1988). Conceptions of second year university students of some fundamental notions in chemistry. *International Journal of Science Education,* 10(3), 331-336.

Cros, D., Maurin, M., Amouroux, R., Chastrette, M. & Leber, J. (1986). Conceptions of first year university students of the constituents of matter and notions of acids and bases. *European Journal of Science Education,* 8(3), 305-313.

Demerouti, M., Kousathana, M. & Tsaparlis, G. (2004) Acid-base equilibria, Part I. Upper secondary student's misconceptions and difficulties. *The Chemical Educator,* 9, 122-131

Demircioğlu, G., Ayas, A. & Demircioglu, H. (2005) Conceptual changes achieved through a new teaching program on acids and bases. *Chemistry Education Research and Practice,* 6(1), 36-51 http://www.rsc.org/images/p3_Demircioglu_tcm18-31135.pdf [Retrieved 31st March 2009]

Demircioğlu, G., Özmen, H. & Ayas, A. (2004) Some concepts misconceptions encountered in chemistry: a research on acid and base. *Educational Sciences: Theory and Practice,* 4(1), 77-80

Dhindsa, H. S. (2002) Preservice teachers' conceptions of pH. *Australian Journal of Education in Chemistry,* 60, 19-24

Drechsler, M. & Schmidt, H.-J. (2005a). Textbooks' and teachers' understanding of acid-base models used in chemistry teaching. *Chemistry Education Research and Practice,* 6(1), 19-35 from http://www.rsc.org/images/p2_drechsler_tcm18-31134.pdf [Retrieved 31st March 2009]

Drechsler, M. & Schmidt, H.-J. (2005b). Upper secondary school students' understanding of models used in chemistry to define acids and bases. *Science Education International*, 16(1), 35-53.

Erduran, S. (2003) Examining the mismatch between pupil and teacher knowledge in acid-base chemistry. *School Science Review*, 84(308), 81-86

Furió-Más, C., Calatayud, M.-L. & Bárcenas, S. L. (2007). Surveying students' conceptual and procedural knowledge of acid-base behaviour. *Journal of Chemical Education*, 84(10), 1717-1724. Supplemental material from http://jchemed.chem.wisc.edu/Journal/Issues/2007/Oct/ [Retrieved 8th February 2008]

Hand, B. M. & Treagust, D. F. (1988). Application of conceptual conflict strategy to enhancing student learning of acids and bases. *Research in Science Education*, 18, 53-63.

Hand, B. M. (1989) Students' understanding of acids and bases: A two year study. *Research in Science Education*, 19, 133-144

Kousathana, M. Demerouti, M. & Tsaparlis, G. (2005). Instructional misconceptions in acid-base equilibria: An analysis from a history and philosophy of science perspective. *Science and Education*, 14, 173-193.

Lambert, J. (2005) Students' conceptual understanding of science after participating in a high school marine science course. *Journal of Geoscience Education*, 53(5), 531-539 http://nagt.org/files/nagt/jge/abstracts/lambert-v53n5.pdf [Retrieved 11th February 2007]

Lin, J.-W. & Chiu, M.-H. (2007a). Exploring the characteristics and diverse sources of students' mental models in acids and bases. *International Journal of Science Education*, 29(6), 771-803.

Lin, J.-W., Chiu, M.-H. & Liang, J.-C. (2004) Exploring mental models and causes of students' misconceptions in acids and bases. http://web.cc.ntnu.edu.tw/~jwlin/NARST_2004_ed.pdf [Retrieved 12th June 2006]

Linke, R. D. & Venz, M. L. (1979). Misconceptions in physical science among non-science background students: II. *Research in Science Education*, 9, 103-109.

Nakhleh, M. B. (1994) Students' models of matter in the context of acid-base chemistry. *Journal of Chemical Education*, 71(6), 495

Nakhleh, M. B. & Krajcik, J. S. A. (1993) Protocol analysis of the influence of technology on Students' actions, verbal commentary, and thought processes during the performance of acid base titrations. *Journal of Research in Science Teaching*, 30(9), 1149-1168

Nakhleh, M. & Krajcik, J. S. (1994) Influence of levels of information as presented by different technologies on student understanding of acid-base and pH concepts. *Journal of Research in Science Teaching*, 31, 1077-1096.

Ogunniyi, M. & Mikalsen, O. (2004) Ideas and process skills used by South African and Norwegian student to perform cognitive tasks on acids, bases and magnetism. *African Journal of Research in Science, Mathematics and Technology Education*, 8(2), 151-164

Ouertatani, L., Dumon, A., Trabelsi, A. & Soudani, M. (2007) Acids and bases: The appropriation of the Arrhenius model by Tunisian Grade 10 students. *International Journal of Science and Mathematics Education*, 5, 483-506.

Oversby, J. (2000b). Is it a weak acid or a weakly acid solution? *School Science Review*, 81(297), 89-91

Pinarbasi, T. (2007) Turkish undergraduate students' misconceptions on acids and bases. *Journal of Baltic Science Education* 6(1) 23-34 http://web.ebscohost.com/ehost/pdf?vid=8&hid=105&sid=71c0dd41-75cc-48d3-80a24a5f46b77d23%40sessionmgr102 [Retrieved 11th December 2007]

Ross, B . & Munby, H. (1991). Concept mapping and misconceptions: a study of high-school students' understanding of acids and bases. *International Journal of Science Education*, 13(1), 11-23.

Schmidt, H.-J. (1991) A label as a hidden persuader: chemists neutralisation concept. *International Journal of Science Education*,13(4), 459-471

Schmidt, H.-J. (1995) Applying the concept of conjugation to the Brønsted theory of acid – base reactions by senior high school students from Germany. *International Journal of Science Education*, 17 (6), 733-741

Schmidt, H.-J. & Volke, D. (2003). Shift of meaning and students' alternative concepts. *International Journal of Science Education*, 25(11), 1409-1424.

Sheppard, K. (2006) High-school students' understanding of titrations and related acid-base phenomena. *Chemistry Education Research and Practice*, 7(1), 32-45 http://www.rsc.org/images/Sheppardpaper_tcm18-46455.pdf [retrieved 20th December, 2008]

Smith, K & Metz, P (1996) Evaluating student understanding of solution chemistry through microscopic representations. *Journal of Chemical Education*, 73, 233-235

Sumfleth, E. (1987). Über den Zusammerhang zwischen Schullenistung und Gedächtnis-stuktur-Eine Untersuchung zum Thema Säure-Base – Reaktionen. *Natuurwissen-schaften im Unterricht.* 35, 29-35 cited by Schmidt (1995)

Tan, K. C. D., Goh, N. K, Chia, L. S. & Treagust, D. F. (2002) Development and application of a two-tier multiple choice diagnostic instrument to assess high school students' understanding of inorganic chemistry qualitative analysis. *Journal of Research in Science Teaching*, 39(4), 283-301

Toplis, R. (1998). Ideas about acids and alkalis. *School Science Review*, 80(291), 67-70.

Vidyapati, T. J. & Seetharamappa, J. (1995). Higher secondary school students' concepts of acids and bases. *School Science Review*. 77 (278), 82-84.

Watters, D. J. & Watters, J. J. (2006) Student understanding of pH. *Biochemistry and Molecular Biology Education*, 34(4), 278-284

Ye, R. & Wells, R. R. (1998) Student concept changes in acids and bases. *Proceedings of the National Science Teacher Association National Convention, Las Vegas, Nevada*. ERIC document Ed 425 060.

Zoller, U. (1996) The use of examinations for revealing and distinguishing between students' misconceptions, misunderstandings and no conceptions in college chemistry. *Research in Science Education*, 26(3), 317-326

APPENDIX 2 PREVIOUS PAPERS

Publication 1:

In C. Malcolm & C. Lubisi (Eds) *Proceedings of the South African Association For Research Into Mathematics, Science And Technology Education Annual Conference*, January 2002 Durban, South Africa.

Student difficulties with different models in acid-base chemistry

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Abstract

Brönsted & Lowry's protolysis model of acid-base chemistry necessitates students' visualization of ionic and molecular species in equilibrium. Students also experience difficulty when new conceptual models are superimposed on top of old ones. Student difficulties with different acid-base models and visualization of sub-microscopic particles were investigated through a meta-analysis of published data and a two-phase probe of high school students. The difficulties revealed were compared with propositional statements of scientifically correct concepts. Results showed that students tend to retain a macroscopic view of acid and bases as substances, rather than particles that can donate or accept protons. They also manipulate formulae with little understanding of the sub microscopic particles involved. Some of these difficulties are now well established.

Introduction

In 1990 Pickering showed that when students are taught chemical processes with an emphasis on the particulate nature of matter, and assessed accordingly, their conceptual knowledge improves dramatically. Johnstone (1991) also emphasised that chemistry should be taught on three levels; namely macroscopically, sub-microscopically and symbolically.

In the topic of acid – base chemistry, Carr (1984) stated that student difficulties are "more usually perceived in terms of confusion about models used in teaching the concept than as a conflict between preconceptions and the scientific view." In addition, Ringes (1995) found that when chemistry students are presented with different conceptual models for reduction and oxidation, they tend to persist with the first or become confused between models. In 1992, Hawkes had put forward arguments for teaching students only one model of acid-base to avoid this sort of confusion. The changing nature of the topic of acids and bases, in terms of the different historical models that are frequently layered one upon the other, has been presented by both Carr (1984) and de Vos and Pilot (2001). A major conceptual change in the 1920's took acids and bases from substances to be found in bottles to Brönsted (1926) and Lowry's (1923) definitions in terms of molecules or ions. With this, it became essential for students to visualize the sub-microscopic particles in a reaction in order to make sense of the concepts. Initially students are presented with the macroscopic, qualitative, physical properties of acidic substances. This is followed by formulae and equations about these substances, followed in later years by the theoretical models developed by Arrhenius and Brönsted & Lowry.

Aim

The aim of this study was to investigate students' conceptual and visualisation difficulties with two aspects of acid-base chemistry.

(1) The three different models for acids and bases: the practical-sensory model (substances in bottles), Arrhenius' model (substances which dissociate into ions in aqueous solution) and the Brönsted-Lowry model (molecules or ions that accept or donate protons, becoming ions or molecules in the process).

(2) The three levels at which chemistry can be visualized: macroscopic, sub-microscopic and symbolic.

To achieve this, a list of scientifically accepted propositional statements of the relevant concepts and principles of acid – base chemistry at a grade 12 level was constructed; a meta-analysis of literature for known difficulties with acid-base models was performed; and a research study on grade 12 pupils was carried out to look for evidence of any difficulties with visualisation of the models or the sub-microscopic particles in the reactions.

Methods

Propositional statements

Scientifically correct propositional statements of concepts, principles and definitions used in acid-base chemistry were compiled from various textbooks and published literature. These statements were used to clarify and check the validity of the various student difficulties reported in the literature and found in the research study on grade 12 pupils.

Meta-analysis and classification of published difficulties

An extensive literature search was performed to find papers documenting research into student conceptual difficulties with the topic of acids and bases. A meta-analysis of the documented difficulties was performed according to the method of Cohen *et al.* (2000). This consisted of extracting the evidence for the different difficulties from each paper, and using the propositional statements to clarify and document their descriptions. The difficulties were then classified on the four-level framework of Grayson *et al.* (2001) according to the amount of information known about each difficulty. Thus, difficulties identified in a number of contexts and for which there is a stable description were classified at level 4 or as "established", those identified in limited contexts with descriptions still open to change were classified at level 3 (partially established), those suspected by researchers on the basis of teaching experience but not systematically investigated as "suspected" (level 2), and those which emerge during data analysis as "unanticipated" at level 1**.**

Research study on grade 12 pupils

In order to elicit further information about student difficulties with the acid-base models as well as their ability to visualize the processes at a sub-microscopic level, a research study was carried out. This was conducted in two phases on grade 12 high school students. In the first phase, two free-response type probes, shown in Figure 1, were given on consecutive days to a mixed ability group of 20 to 25 girls who had recently received instruction in acids and bases. They received no feedback between the probes. Student responses to the probes were analysed using the inductive method given by Grayson *et al.* (2001); the categories of difficulties being allowed to emerge as the analysis proceeded. Some categories were eventually combined, reclassified or made into subcategories

1. For each of the substances shown above (NaOH, NH_3, $NaHCO_3$, HBr) write down:
    a) How it will react, if at all, when added to water.
    b) Explain how you worked out your answer to (a).

2. Use your imagination! Imagine you have a very powerful microscope. With this microscope you can SEE all the particles in a solution. What would you SEE when each of the following is added separately to a beaker of water? (Concentrated sulphuric acid, concentrated ethanoic acid, ammonia, potassium hydroxide pellets) [A blank space was provided for the response.]

Figure 1. Phase 1 probes given to 20 - 25 girls in grade 12

In the second phase, four months later, the free response probes shown in Figure 2 were given to a small sample of 11 of the girls, who had participated in phase 1 of the study, while revising for their final examination. Further information was sought about difficulties with visualizing the chemical processes occurring. In addition, the misuse of terms such as dissociation, ionization and hydrolysis was investigated further through asking for diagrams as well as explanations. Further data was also needed on students' reasoning with the equilibrium system of weak acids and bases in water, so it was decided to state explicitly which of these were strong or weak. Two copies of diagram (a) of Figure 2 were given to students - one for question 1. involving HCl, and the second one for question 2. involving NH_3.

1. The gas HCl can be classified as a strong acid. The gas, hydrogen chloride is bubbled into water. Sketch the situation before and after, showing the particles that would be found in the gas tube and beakers. (Diagram a)
2. NH_3 can be classified as a moderately weak base. The gas, ammonia is bubbled into water. Sketch the situation before and after, showing the particles that would be found in the gas tube and beakers. (Diagram a)
3. The contents of the two beakers, from 1 and 2 (hydrogen chloride and ammonia) are mixed. Sketch the final situation showing the particles that would be found in the large beaker. (Diagram b)
4. A spatula of ammonium chloride crystals is added to water. Sketch the situation showing the particles that would be found in the beaker. (Diagram c)

After each sketch, students were asked, "Explain the reasons for choosing the diagrams you did. Please give more than a chemical equation."

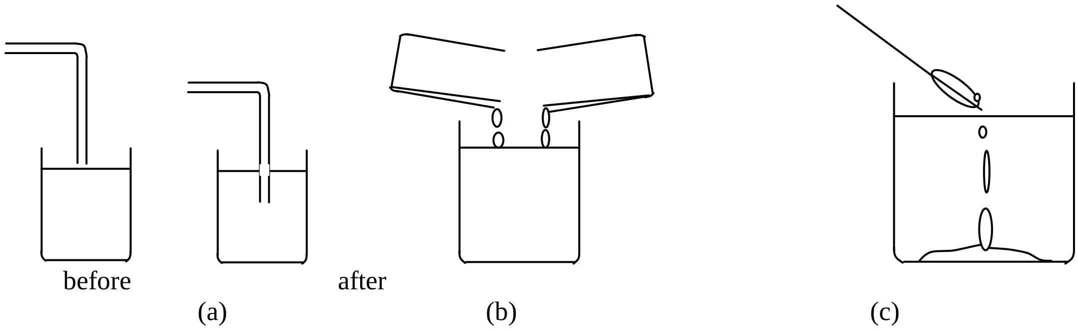


Figure 2. Phase 2 probes given to eleven grade 12 pupils four months after the phase 1

Results And Discussion

Meta-analysis of Published Difficulties

Tables 1 and 2 summarise the information from the meta-analysis of the difficulties already published in the literature. The description of the difficulty is a statement of students' alternative conception: this is contrasted with a propositional statement. Only those difficulties relevant to this study are presented here.

Description of Difficulty	Propositional Statement by Authors	C*	Reference for Difficulty
Acids and bases are substances	Brönsted – Lowry acids and bases are particles that can donate or accept protons.	2	Sumfleth (1987)
Acids have pH < 7 Bases have pH > 7	Acids are proton donors, bases are proton acceptors. (ie particles, Bronsted – Lowry)	4	Cros *et al* (1986 & 1988)
Bases produce OH^- ions	Bases are proton acceptors	4	Cros *et al* (1986 & 1988)
Acids contain OH^- ions	Acids are proton donors, they must contain hydrogen atoms.	3	Ross & Munby (1991)
Bases are contained in acids	Bases are proton acceptors	2	Hand & Treagust (1989)
C* = Classification on framework of Grayson *et al.*, 2001			

Table 1. Difficulties and propositional statements pertaining to acid and base definitions

The first difficulty in Table 1. reflects students' macroscopic view of acids and bases as substances, while the second give these substances certain pH ranges. These difficulties appear to indicate that these students have persisted with the macroscopic model despite having been subsequently taught the theoretical, sub-microscopic models before or during their first year at university when Cros *et al*. (1986 & 1988) carried out their study. The third difficulty shows students have retained the Arrhenius model while those who show the last two difficulties appear to have become confused between Arrhenius' model and the Brönsted-Lowry model. Carr (1984) warns against this danger and cautions that changes in models be "clearly signposted".

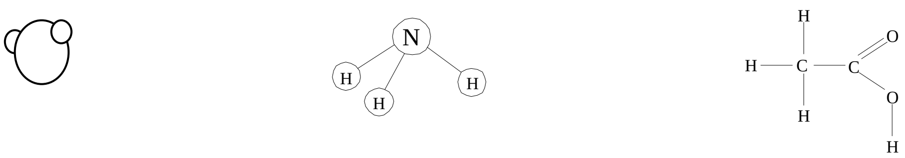
Description of Difficulty	Propositional Statement by Authors	C*	Reference For Difficulty
Neutralisation is a double decomposition reaction.	Neutralisation is a proton transfer reaction producing water.	2	Nakhleh & Krajeik (1993)
The product of neutralisation is not water, $OH(H_3)$ or H_4O formed.	Water molecules, H_2O, are produced during neutralisation.	2	Nakhleh & Krajeik (1993)
Every neutralization reaction produces a neutral solution.	If weak acids or bases are involved, reactions between stochiometric amounts will yield non-neutral solutions	4	Schmidt (1991 & 1997)
Neutralization gives a solution with equal concentrations of H_3O^+ and OH^- ions	If weak acids or bases are involved, reactions between stochiometric amounts will yield solutions with excess H_3O^+ or OH- ions	4	Schmidt (1991)
H_3O^+ and OH^- react completely and there are no H_3O^+ and OH^- ions remaining after neutralization.	There will always be some H_3O^+ and OH^- ions since $K_w = [H_3O^+].[OH^-]$	4	Schmidt (1995 & 1997)
Aqueous solutions of salts are neutral and do not contain H_3O^+ and OH^-	There will always be some H_3O^+ and OH^- ions since $K_w = [H_3O^+].[OH^-]$	4	Schmidt (1991)
Aqueous solutions of salts are neutral since $[H_3O^+] = [OH^-]$	Hydrolysis can occur, depending on the acid-base strength of anion or cation.	4	Schmidt (1991)
C* = Classification on framework of Grayson *et al.*, 2001			

Table 2. Difficulties and propositional statements pertaining to neutralisation and ions

Table 2. shows student difficulties with ionic concepts in acid – base chemistry. Students describing acid-base reactions as double decomposition do not appear to use proton transfer mechanisms in their reasoning, and are possibly simply manipulating chemical formulae: as do students who write impossible formulae such as H_4O for the products of the reaction. Schmidt's studies have also established reasoning difficulties based on terminology. Words such as "neutralisation" conjure up the notion of a neutral solution. The term neutralisation is historical, based on the ability of acids to "consume" bases and has little relevance in the Brönsted-Lowry model. Schmidt (1991) studied the difficulties among grammar school students and suggested that they neglect hydrolysis and chemical equilibrium in their reasoning strategies, or think of salts as the product of neutralisation, and so assume they must be neutral. Teachers should be encouraged to anticipate the possibility of these reasoning difficulties with their students.

Research study on grade 12 pupils

The results of the two phase study on grade 12 students which are relevant to acid – base models and ability to visualize the sub-microscopic chemistry taking place are summarised in Tables 3. In all probes it was expected that students would show particles as stereochemical (space filling or ball and stick models) or a structural formulae (Figure 3). More than one particle would be acceptable in each case.



water molecule

ammonia molecule

ethanoic acid molecule

Figure 3. Possible acceptable types of diagrams of particles in Phase 1 and 2 probes.

Code	Description of Difficulty	Percentage Incidence					
		Phase 1 (Fig1) Probe Number		Phase 2 Question Number (N = 11)			
		1 (N=25)	2 (N=20)	1	2	3	4
Difficulties with visualisation of particles							
V1	No attempt made at particulate drawings or description	100	15	0	0	0	18
V2	Particles shown by formulae alone	-	15	55	64	64	64
V3	Particles shown by formulae enclosed by a ring	-	-	36	27	27	27
V4	Particles shown with coefficient from equation, 2HCl	-	-	9	0	0	0
V5	Particles are visualized as part of equations.	100	60	0	0	9	0
Difficulties with formulae and symbols							
N1	Single example of each type of particle considered or shown	-	15	9	36	45	45
S1	Number of atoms/ particles is non-stochiometric	28	5		36	9	9
S2	Charge is not conserved in a chemical reaction	40	25				
Difficulties with acid – base terminology							
T1a	Ionization shown and dissociation described	12	15	9			
T1b	Dissociation shown and ionization described	12	-				
T2a	Hydrolysis shown and dissociation described	4	-			9	
T2b	Dissociation shown and hydrolysis described	12	5				
T3	Decomposition shown and dissociation described	8	-				36
T4	Ionization shown and hydrolysis described	20	-				
Difficulties with models for acids & bases							
Vol 1	A solution is described in terms of the substance dissolved	28	15			73	
Vol 2	Acid-base reaction is not H_3O^+ (or H^+) + OH^-					18	
Vol 3	Aqueous solutions of salts are neutral since there are no H_3O^+ or OH^- ions						45
BL	Substances that contain hydrogen are acids.	24	-	9			
ArA	Acids dissociate in water to form H^+ ions	20	30				
ArB	Bases produce OH^- ions in water	4	-				
ArBL1	Dissociation and ionization showed in same system			9			

Table 3. Description and incidence of grade 12 student difficulties with acid base-concepts

Student difficulties in visualizing particles showed that these students appear to rely heavily on molecular formulae and symbols, especially with the first probe that used the word "react". Every student appeared to believe that a chemical equation was a necessary part of her explanation. In the second phase, by specifically asking for more than a chemical equation, these probes prompted some sort of drawing from the students. Evidently they had difficulty in thinking about particles as atoms or ions; nearly all of the students still used a formula with or without a ring around it to indicate a "particle" in these reactions (difficulties V2, 55-64% and V3, 27-36%). Their dependence on equations is evident in difficulty V5 shown by the response, "$NH_4Cl + H_2O \rightarrow HCl + NH_3 \rightarrow HCl + H_2O \rightarrow Cl^- + H_3O^+$" being written across a beaker.

Despite student reliance on molecular formulae, some difficulties with the stochiometric numbers of atoms (S1, 5% to 28%) or charge balance (S2, 25% to 40%) were evident in the first probe. In the second phase this difficulty was only evident in the ionization of the weak base ammonia that appeared to be more difficult (difficulty S1, 36%), as shown by the response depicting three ammonium ions and two hydroxide ions.

Students' difficulties with terminology, where the equation given did not match the explanation, were also revealed here. The terms "ionization", "dissociation" and "hydrolysis" were commonly used interchangeably. For example, the ionization of ammonia was shown correctly as "$NH_3 + H_2O \rightarrow NH_4^+ + OH^-$", but explained as "$NH_3$ dissociates in water.." (difficulty T1a, 9% to 15%). A response typical of the confusion between dissociation and decomposition was, "$NH_4Cl + H_2O \rightarrow NH_3 + HCl$" . Since students also studied the thermal decomposition of ammonium chloride, this appears to have become confused with dissociation occurring in aqueous solutions. This could indicate difficulty with visualisation of the ionic particles in water.

Student difficulties with the different models for acids and bases were also evident. A most significant group of student difficulties, classified as Vol 1,2 and 3, appears to show a reasoning strategy that explains reactions in terms of the original substance dissolved in solutions, as when studying volumetric analysis, rather than the ionic species in the solution. A typical response for difficulty Vol 1 (73%) showed HCl and NH_3 ionising correctly in the first two questions, but in question 3, where the contents of these beakers were mixed, the student reverted to, "$HCl + NH_3 \rightarrow NH_4Cl$" - no water was shown at all. Similarly, this neglect of the reaction between hydronium and hydroxide ions (Vol 2) is also shown by 18% of the students.

In the first phase some students were unsure about examples of acids and bases (difficulty BL, 24%), Ross & Munby (1991) also reported this. The ammonia molecule was thought to have acidic properties as shown by, "$NH_3 + H_2O \rightarrow H_3O^+ + NH_2$" or "$NH_3$ is the conjugate acid of NH_4^+". In addition, sodium hydroxide was seen by students to be a proton donor: "NaOH with $H_2O \rightarrow NaO^- + H_3O^+$ NaOH is a strongish acid and therefore it will be able to lose a hydrogen ion easily." Blind application of the Brönsted-Lowry definition to any compound containing hydrogen, without understanding the bonds involved could be the source of this. Teachers need to be aware of this possibility when introducing the theoretical models.

There were also many difficulties showing confusion between models for acids and bases. Difficulty ArA, Arrhenius' model of dissociation, was used by 20% to 30% students to explain the behaviour of an acid with water, for example, "$HBr \rightarrow H^+ + Br^-$". Arrhenius' theory also describes bases as producing OH^- ions in water and this definition evidently persists as shown by the student with difficulty ArB who fell somewhere between Arrhenius' and Brönsted & Lowry's theories when writing, "Na^+ is an acid and NaOH is its conjugate base." Carr cautioned against the possibility of model confusion in 1984.

The difficulties revealed in this study are now partially established – they have been found in a limited context and the descriptions could be open to change. Further investigations in other contexts are needed.

CONCLUSIONS

The meta-analysis of documented difficulties reveals that in acid-base chemistry students do have difficulties with the three levels suggested by Johnstone (1991). The macroscopic view of substances persists and students resist moving from this model to another requiring sub-microscopic understanding of particles. Formulae and symbols appear to be manipulated with little understanding of the theoretical model. Superficial reasoning strategies, relying on intuitive but obsolete meanings of words, are prevalent. There is also evidence that they become confused between two models or retain the one taught earlier as Carr (1984) and Ringes (1995) found. Since many of these student difficulties are established at level 4, teachers need to be aware of these when planning their teaching strategies.

The students probed in this project showed little use of a reasoning strategy that visualized ions and molecules in chemical reactions. It is probable that they have not accommodated the Brönsted -Lowry model for acids and bases. They appear to still use a practical, sensory model with associated molecular symbolism. They do not appear to transfer principles learned in chemical equilibrium, bonding and structural formulae into acid-base chemistry. Further research will be needed to investigate this aspect.

References

Brönsted, J.N.: 1926, 'The acid-base function of molecules and its dependency on the electric charge type', *Journal of Physical Chemistry* **30**, 777-790.

Carr, M.: 1984, 'Model confusion in chemistry'. R*esearch in Science Education,* **14**, 97-103.

Cohen, L., Manion, L. and Morrison, K.: 2000, *Research Methods in Education*. 5th ed. Routledge - Falmer London & New York.

Cros, D., Maurin, M., Amouroux, R., Chastrette, M. and Leber, J: 1986, 'Conceptions of first year university students of the constituents of matter and notions of acids and bases', *European Journal of Science Education* **8**(3) 305 – 313

Cros, D., Chastrette, M., and Fayol, M.: 1988, 'Conceptions of second year university students of some fundamental notions in chemistry' *International Journal of Science Education*, **10**(3) 331-336

de Vos, W. and Pilot, A.: 2001, 'Acids and bases in layers: The stratal structure of an ancient topic', *Journal of Chemical Education*, **78**(4) 494-499

Grayson, D.J., Anderson, T.R., and Crossley, L.G.:2001, 'A four-level framework for identifying and classifying student conceptual and reasoning difficulties', *International Journal of Science Education* 23(6) 611-622.

Hand, B.M. and Treagust, D.F.: 1988 'Application of conceptual conflict strategy to enhancing student learning of acids and bases', R*esearch in Science Education***, 18** 15-63

Hawkes, S.J.: 1992, 'Arrhenius confuses students', *Journal of Chemical Education*, **69**(7) 542-543

Johnstone, A. H.: 1991, 'Why is science difficult to learn? Things are seldom what they seem', *Journal of Computer Assisted Learning,* **7**, 75-83

Lowry, T.M.: 1923, 'Co-ordination and acidity', *Chemistry and Industry,* **42** 1048-1052.

Nakhleh, M. B. and Krajeik, J. S. A.: 1993, 'Protocol analysis of the influence of technology on students' actions, verbal commentary, and thought processes during the performance of acid base titrations', *Journal of Research in Science Teaching,* **30**(9) 1149-1168

Pickering, M.: 1990, 'Further studies on Concept learning versus Problem Solving', *Journal of Chemical Education,* 63(3) 254 – 255

Ringes, V., 1995, 'Oxidation-reduction – learning difficulties and choice of redox models', *School Science Review*, **77**(279) 74-75

Ross, B. and Munby, H.: 1991, 'Concept mapping and misconceptions: A study of high-school students' understanding of acids and bases', *International Journal of Research in Science Education,* **13**, 11-23

Schmidt, H-J.: 1991, 'A label as a hidden persuader: Chemists' neutralization concept', *International Journal of Science Education,* **13**(4) 459-471

Schmidt, H-J.: 1995, 'Applying the concept of conjugation to the Brönsted theory of acid-base reactions by senior high school students from Germany', *International Journal of Science Education,* **17**(6) 733-741

Schmidt, H-J.: 1997, 'Student Misconceptions – Looking for a pattern', *Science Education,* **81**(2) 123-135

Sumfleth, E. and Telgenbüscher, L., 2001, Improving the use of instructional illustrations in learning chemistry. *Research in Science Education – Past Present and Future*, 289-294, Kluwer Academic Publishers

Sumfleth, E. (1987). Über den Zusammerhang zwischen Schullenistung und Gedächtnis-stuktur-Eine Untersuchung zum Thema Säure-Base – Reaktionen. *Natuurwissen-schaften im Unterricht.* 35, 29-35 cited by Schmidt (1995)

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FORMULATION OF STATEMENTS OF PROPOSITIONAL KNOWLEDGE AND CORRESPONDING STUDENT DIFFICULTIES FOR THE BRØNSTED-LOWRY ACID-BASE MODEL: A RECIPROCAL MATCHING AND HONING PROCESS

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Abstract

Propositional knowledge statements of scientifically accepted conceptions have been advocated by various authors as comparative controls in the identification of students' alternative conceptions in science. However, to our knowledge, the process by which propositional statements are formulated and used to hone an accurate description of such student difficulties, and vice versa, has not been described. The aim of this study was to investigate this approach as applied to the topic of the Brønsted-Lowry model of acid-base chemistry. Formulation of a set of propositional statements representing the historically accurate model involved collating statements from current literature and historical publications, classifying them according to chemical representation systems, namely: macroscopic, microscopic and symbolic, then expanding, rearranging and clarifying them according to devised criteria. Simultaneously, these statements were reciprocally matched to corresponding descriptions of student difficulties gleaned from previously published studies, and the results showed that this process was important in the formulation and clarification of both propositional statements and the descriptions of corresponding alternative student conceptions. Furthermore, propositional statements prepared in this way could form a foundation for curriculum and textbook design and help prevent or remediate difficulties due to hybrid models in students.

INTRODUCTION

Student difficulties in acid-base chemistry have apparently received little attention in the literature. Unlike the particulate nature of matter and electrochemistry, which each generated more than 20 descriptions of student alternative conceptions, a recent research review presented only five misconceptions in acid-base chemistry (Barker, 2001). Garnett, Garnett and Hackling (1995) emphasised the need for more research in the acid-base topic and suggested "a list of conceptual and propositional knowledge statements ... would provide a sound starting point." These statements, used as comparative controls of "accepted scientific understanding" have often received less attention in research papers than have the descriptions of students' alternative conceptions. Tension between expert scientific views and the need to present concepts simply enough for younger students implied some compromise (de Vos & Verdonk, 1996). However, Justi and Gilbert (1999) warned against teaching students "hybrid models" and showed their prevalence in textbooks. Such a hybrid model has often been presented under the guise of the Brønsted-Lowry acid-base model (Carr, 1984; de Vos & Pilot, 2001).

Research Aims

This research project addressed the following research questions:

1. What propositional knowledge corresponding to the various representations of the Brønsted-Lowry model is expected of high-school students and what process should we use to formulate statements of such knowledge?
2. Can the formulated propositional statements be used to hone and clarify the nature of the student difficulties, and vice versa, and what process could achieve this?

To achieve these aims we first outlined the criteria for a set of propositional knowledge statements. Then we developed a set of propositional statements describing the Brønsted-Lowry acid-base model that met these criteria. Alongside this, descriptions of student misconceptions was extracted from published literature and examined in terms of the statements. Cross-checking between the two lists was necessary as they illuminated each other. Descriptions describing the nature of student difficulties were then synthesised.

Research Methods

Formulation of Propositional Knowledge Statements

We devised the following criteria to judge the set of propositional statements formulated in this study. These should:

1. Present the expressed model in its specific context, making its limitations obvious.
2. Be as close to expert knowledge as is practical, bearing in mind the stage of the students' understanding.
3. Have sufficient detail to enable students to explain the required phenomena.

We focused on the Brønsted-Lowry model that is commonly found in high school texts. Our starting point was a synopsis of textbook presentations of the model published by Nakhleh and Krajcik (1994). It separated the statements according to chemical representational systems, namely: macroscopic, microscopic, symbolic and algebraic. We needed to make subtle, although significant, changes to the wording of these original statements so they would meet our criteria. To ensure consistency within the Brønsted-Lowry model, we compared the original set of statements to the Brønsted-Lowry context outlined by de Vos & Pilot (2001). Any disagreements were resolved by consulting original papers (Brønsted, 1926; Brønsted & Guggenheim, 1927; Lowry, 1923), historical studies (Bell, 1969) and the IUPAC (1997) definitions for modern expert knowledge. In order to ensure the list was appropriate for South African students, we compared it with the learning outcomes for Grade 12 examinations (IEB, 1997) and supplemented it where necessary.

Synthesis of Descriptions of Student Difficulties

References to published studies on student difficulties in acid-base chemistry were found through online electronic indexes. Information on individual student difficulties was extracted from each article. Once corresponding propositional statements (sometimes more than one) were matched with each student difficulty, groups of similar statements of these difficulties emerged quickly. When compared with the propositional statements, a concise description of the particular student difficulties in each category could be synthesised. On some occasions, study of the student difficulty led to clarification of the set of propositional statements. It was a two-way or reciprocal process.

RESULTS AND DISCUSSION

Formulation of propositional knowledge statements

Tables 1, 2 and 3 show the list of statements formulated in this study. For simplicity, the explanation of indicators' colour change (IEB, 1997) and the "Algebraic System", involving calculations and pH graphs (Nakhleh & Krajcik, 1994), have not been reported.

Table 1. *Propositional Knowledge Statements for Brønsted -Lowry acid–base model: Macroscopic representation (Properties of substances)*

1) Characteristics of acidic substances.
    a) They change the colour of appropriately chosen indicators, e.g. litmus – blue to pink; bromothymol blue – blue to yellow; phenolphthalein – pink to colourless; methyl orange – yellow to red.
    b) They taste sour / sharp like lemons or sour milk.
    c) In aqueous solutions of the same concentration, strong acids are better conductors of electricity than weak acids.
2) Examples
    a) Acids are found in many foods, e.g. vinegar (ethanoic/ acetic acid), citrus fruit (citric acid), milk (lactic acid) apples & pears (malic acid).
    b) Common laboratory acids include hydrochloric acid, ethanoic/ acetic acid, nitric acid and sulfuric acid. These are usually used in aqueous solution.

3) Characteristics of basic substances.
    a) They change the colour of appropriately chosen indicators, e.g. litmus – pink to blue, bromothymol blue – yellow to blue, phenolphthalein –colourless to pink and methyl orange – red to yellow.
    b) They sometime taste bitter like soap.
    c) They feel soapy in aqueous solutions.
    d) In aqueous solutions of the same concentration, strong bases are better conductors of electricity than weak bases.
4) Examples
    a) Bases are commonly found in the household, e.g. baking soda, oven cleaners and soaps.
    b) Basic substances commonly found in a laboratory include ammonia, potassium hydroxide, calcium hydroxide and sodium carbonate. These may be used in aqueous solutions.
5) A soluble metal hydroxide is called an alkali.

6) Acidic substances in dilute aqueous solutions react (usually exothermically) with:
    a) Basic substances, losing their acidic properties through neutralisation. For example, with:
        (i) A metal oxide to form a salt and water.
        (ii) A metal hydroxide to form a salt and water.
        (iii) A metal carbonate to produce a salt, water and carbon dioxide.
    b) Active metals to form a salt and hydrogen.
7) Amphoteric substances have both acidic and basic properties.
8) Concentrated acidic and basic substances undergo vigorous and dangerous chemical reactions. These may be highly exothermic, dehydrating or oxidising.
9) A titration is a laboratory procedure in which measured volumes of a solution of one substance are added to a definite amount of a second substance in solution, until the reaction between them is complete. The end point of the reaction is usually judged by the colour change of a suitable indicator.

10) The pH scale relates to both acidity and basicity of aqueous solutions.
    a) Acidic solutions have a pH < 7. Lowest values indicate the most acidic solutions.
    b) Basic solutions have a pH > 7. Highest values indicate the most basic solutions.
    c) Neutral solutions have a pH of 7.

Table 2. *Propositional Statements for Brønsted -Lowry acid–base model: Microscopic representation (Characteristics of Particulate Species)*

11) An acid is a particulate species capable of donating a proton (a hydrogen ion) to a base; e.g. hydrogen chloride molecule, ammonium ion, water molecule, hydronium ion.
12) A base is a particulate species capable of accepting a proton (hydrogen ion) from an acid; e.g. chloride ion, hydrogen carbonate ion, ammonia molecule, water molecule, hydroxide ion.
13) Proton transfer (protolysis) can only take place when both acid and base are present. The products are the respective conjugate base and acid as shown alongside.

acid 1 + base 2 or $\overset{\longrightarrow}{\rightleftarrows}$ base 1 + acid 2

14) In the same solvent:
    a) Stronger acids release protons to bases more readily than do weaker acids, which tend to form equilibrium systems.
    b) Stronger bases accept protons from acids more readily than do weaker bases, which tend to form equilibrium systems.
15) Amphiprotic/amphoteric species can act either as acid or base, depending on the relative strength of the other reactant.
16) Water is amphoteric and ionises itself to a small extent.
17) pH is a measure of the hydrogen ion concentration in an aqueous solution.
    a) A low pH indicates a high hydrogen ion concentration.
    b) A high pH indicates a low hydrogen ion concentration.
18) Electrical conductivity of acidic or basic solutions is due to the presence of ions.
19) A salt is a chemical compound consisting of an assembly of cations and anions (IUPAC, 1997).

Table 3. *Propositional Knowledge Statements for the Brønsted -Lowry acid–base model: Symbolic Representations*

20) Chemical formulae convey information about the number of atoms that make up a molecule or ion.
21) Every acid formula has a hydrogen atom that can be released as a proton. Polyprotic acids contain more than one releasable hydrogen atom per molecule.
22) Acid formulae can represent:
    a) The substance, e.g. $HCl(g)$, $CH_3COOH(l)$, $(COOH)_2(s)$
    b) A solution of the substance, e.g. $H_2SO_4(aq)$, $HNO_3(aq)$,
    c) Particulate species, e.g. molecules HCl, H_2O, or ions HCO_3^-, NH_4^+
23) Bases have formulae with a proton acceptor group. These can represent:
    a) Basic substance, e.g.: $NH_3(g)$, $NaOH(s)$, $Mg(OH)_2(s)$, and $Na_2CO_3(s)$.
    b) A solution of the substance, e.g. $KOH(aq)$, $Ca(OH)_2(aq)$ and $K_2CO_3(aq)$.
    c) Particulate species, e.g. molecules H_2O, NH_3 or ions OH
24) The solvated proton can be represented as, for example in water, $H^+(aq)$ or H_3O^+ or $H_3O^+(aq)$.
25) Conjugate acid-base pairs have formulae that differ by one proton, e.g. NH_4^+ and NH_3.
26) Water is partly ionised and $[H^+(aq)].[OH^-(aq)]$ is a constant at a given temperature.

27) pH of dilute solutions can be calculated from the formula: $pH = -\log_{10}[H^+]$.
28) The end point of a titration occurs when stoichiometric amounts of acid and base are present. The solution will only be neutral if acid and base are equally strong.

The statements in Tables 1 to 3 were formulated according to a specific process. Screening the original synopsis of propositional knowledge statements (Nakhleh & Krajcik, 1994) according to the defined criteria led to the expansion, rearrangement and clarification of the original statements, as follows.

Expansion of the List of Propositional Statements

We expanded the original 18 published statements (Nakhleh & Krajcik, 1994) to 28 by adding new statements and separating others into two or more. This was necessary for two main reasons: to incorporate the requirements for South African students and for greater clarity. As student difficulties were studied, we found it necessary to make each corresponding propositional statement more explicit. We speculate that one reason for students' alternative conceptions could be a lack of such tacit knowledge.

Statements added for South African students include those about electrical conductivity (Statements 1c, 3c and 18), amphoteric substances and the amphiprotic nature of some acids and bases (7 and 15). In response to studies on student difficulties we included statements on the pH scale (10 and 17), conjugate acid-base pairs (13 and 25), ionisation of water (16 and 26), definition of a salt (19) and titration end points (28). Schmidt's (1995, 1997) extensive work among German high school students revealed difficulties in applying the Brønsted-Lowry model to identify acid-base conjugate pairs. He described their alternative conception as "Acid-base conjugate pairs consist of positively and negatively charged ions that can somehow neutralise each other", and speculated that this was due to German textbooks seldom showing the difference between the conjugate and non-conjugate pairs. However, work among South African students showed similar results (Bradley & Mosimege, 1998) and the alternative conception was evidently more widespread. This difficulty necessitated our introducing Propositional Statements 13 and 24 to show the explicit knowledge needed.

A student difficulty with the neutralization reaction also emerged from studies among German high school students (Schmidt, 1991, 1997) as well as Australians at high school and university (Wilson, 1998). Schmidt (1991) put forward the idea that the label "neutralization", which arose in a historical context before Brønsted-Lowry, was a "hidden persuader". These students appear to have knowledge only corresponding to Statement 6 and it showed us the importance of making statements overt as in numbers 13, 14, 16 and 25. This again seems to be a difficulty arising from students using one representation system, rather than linking the three to enrich their understanding of the topic.

Further additions to the list were made to indicate the extent and limitations of a concept. For example, Statements 4b and 23 include examples of carbonates among the bases in response to students' persisting with the more limited Arrhenius definition of a base - releases hydroxide ions - (Cros, Maurin, Amouroux, Chastrette, & Leber, 1986; Nakhleh & Krajcik, 1994; Wilson, 1998). The potentially harmful nature of concentrated acidic or basic solutions is given in Statement 8 in response to the student conceptions that all acids are harmful and that bases are harmless (Hand & Treagust, 1988; Ross & Munby, 1981; Nakhleh & Krajcik, 1994).

Rearrangement of the List of Propositional Statements

In our formulated statements, those about acids have been separated from those about bases. Research has shown that some students have little knowledge of bases (Cros et al., 1986) so we tried to give them equal importance (see Statements 1 and 3). We also included "Brønsted–Lowry" in the heading to all three tables showing that the model can be used with all three representations, provided care is taken with terminology.

Clarification of the List of Propositional Statements

This stage was crucial to maintaining a consistent Brønsted-Lowry model. The subtlety of some of the changes needed to avoid aspects of other acid-base models belies the demanding and stimulating discussion they generated.

It was first essential to clarify the meaning of "acid" or "base" (Statements 11 and 12). IUPAC (1997) gives the current definition of a Brønsted acid as: *A molecular entity or the corresponding chemical species capable of donating a hydron (proton) to a base.* Similarly, a Brønsted base is given as: *A molecular entity or the corresponding chemical species capable of accepting a hydron (proton) from an acid.* Nakhleh and Krajcik's (1994) statements about the abilities of acids to donate protons *to water molecules* and bases to *release hydroxide ions* are remnants of the earlier Arrhenius model, which was limited to aqueous solutions (de Vos & Pilot, 2001). We note the distinction between the two models. Students need a suitable "signpost" to show that the Arrhenius' model is limited to aqueous solutions, while the Brønsted-Lowry model is independent of solvents and has a fundamentally changed definition for a base. The explicit statement about ions or molecules is also necessary to emphasise the move from Arrhenius' macroscopic model for substances to the microscopic model for species (Brønsted & Guggenheim, 1927; Lowry, 1923). In addition, Statement 24, concerning symbolic representations of the proton, was added to indicate that the donated proton cannot exist alone.

We also believe the explanation of acid-base reactions must show that both reactants need to be present. An acid can only donate a proton if there is a base present to receive it (Statements 11, 12, 13 and 15.) On these hinge the explanation for strength of acids or bases. The "dissociation constant" for an acid or base depends on the solvent, as it is the other reactant; there is no absolute strength of acids or bases (Brønsted & Guggenheim, 1927). Limiting statements to aqueous solutions could mislead students. In addition, we have some reservations about the definition of a salt given in Statement 19. Although apparently simple, the IUPAC definition represents a wide range of compounds such as basic salts, acidic salts and coordination compounds. Thus further studies on student difficulties are needed to establish whether it should be narrowed for use at high school.

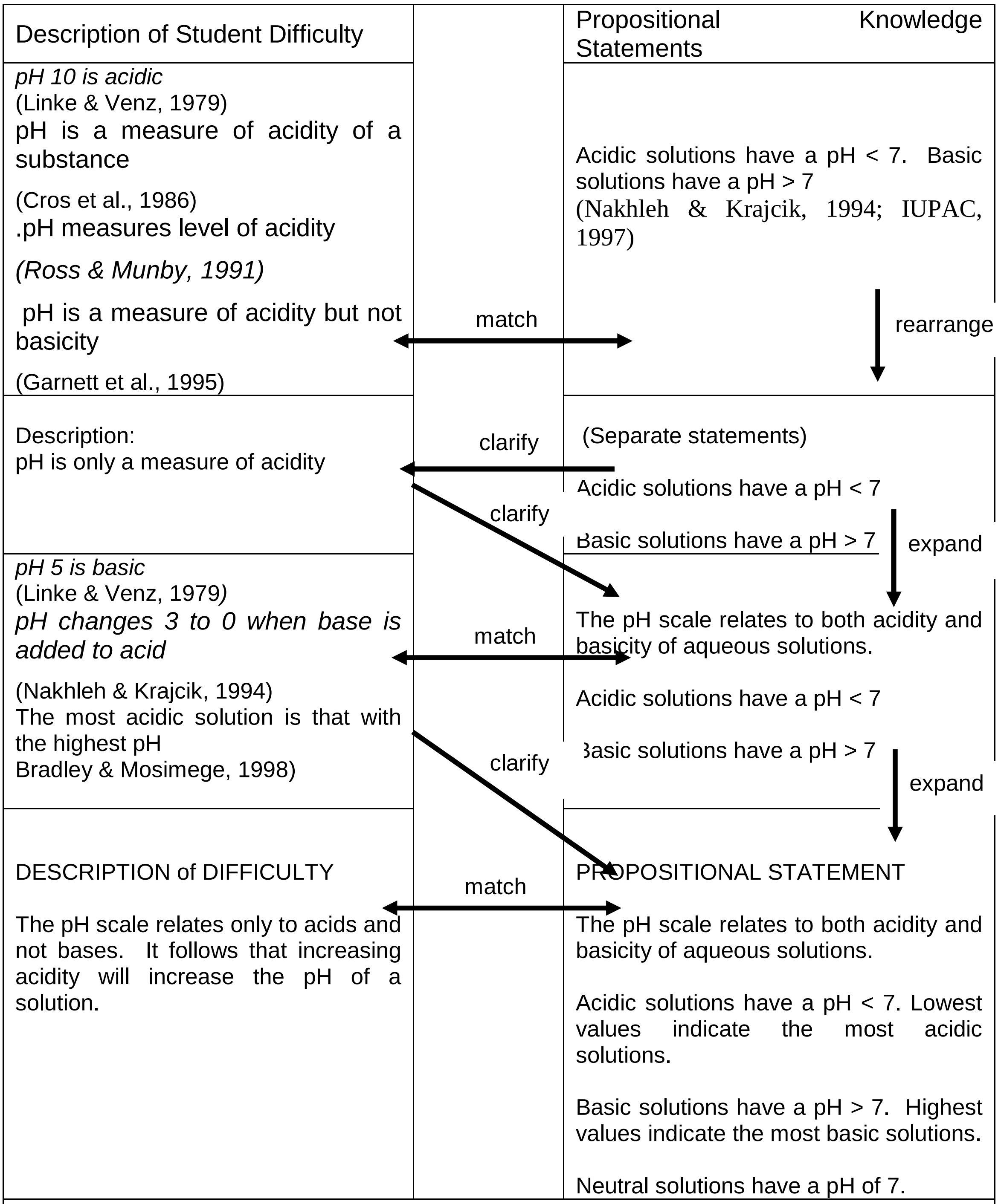
The second major change to the original synopsis was in the language used in each statement. For example, in Table 1, Macroscopic Properties, we avoided reference to "acids" and "bases", using instead "acidic substances" and "basic substances" to maintain consistency of a model that has definitions in the microscopic context. In this model hydroxide ion would be the base, rather than the substance sodium hydroxide. This could help avoid a common alternative conception reported by Anderson (1990) and Selley (2000) where students ascribe the macroscopic proprieties of a substance to its individual molecules or ions. They advocated careful choice of language by teachers.

Similarly, we distinguished substances from the aqueous solutions, so commonly encountered in laboratories. Brønsted (1926) elucidated how a substance such as aluminium oxide can show the acidic properties of a proton donor by discussing the species involved in aqueous solution: these hydrated ions are the actual proton donors. Since pH is a macroscopic measure of solvated hydrogen ion concentration (or activity), it is also misleading to ascribe a pH to pure substances such as “an acid” (IUPAC, 1997). This clarification would enable a student to explain that water *molecules* can act as an acid, even though the *substance* water has a pH of 7. Similarly, although sulfuric acid (the molecular species) is a strong acid (i.e. a good proton donor), the concentrated sulfuric acid on the laboratory bench is hardly ionised at all and is a poor electrical conductor.

Language is also specific for microscopic or macroscopic contexts. In Statement 20 we preferred the words “atoms”, “molecules” and “ions” to the original “atoms” and “compounds”. Sanger’s (2000) study of student conceptions of pure substances and mixtures outlined four acceptable ways to classify matter: in terms of phase, purity, macroscopic composition (element or compound), and microscopic composition (atoms or molecules). An earlier study in acid-base chemistry showed that students resist using a microscopic context in acid-base chemistry (Halstead, Anderson & Spankie, 2002). By making these contexts obvious, teachers could encourage students to see the need for different mental representations in different contexts.

Synthesis of descriptions of student difficulties

The literature search revealed 18 papers on student difficulties with acid-base chemistry. Of the 14 research groups involved, only four reported clear propositional statements of the knowledge expected of students (Ross & Munby, Nakhleh & Krajcik, 1994; Schmidt, 1991, 1995, 1997; Halstead et al., 2002), although most inferred students should use the Brønsted-Lowry model. Figure 1 shows part of the process of reciprocal matching between descriptions of student difficulties with pH and the corresponding propositional statements that we used to clarify and hone both types of statements. The process necessitated rearrangement and two expansions of the propositional statements on pH as they were matched against descriptions of student difficulties. It led eventually to an explicit Propositional Statement which in turn enabled us to synthesise the concise description of the student difficulty as: *The pH scale relates only to acids and not bases. It follows that increasing acidity will increase the pH of the solution.* The difficulty could then be classified at Level 4 on the Grayson et al. (2001) framework as we had a stable description and they have been identified in at least four different contexts. Further difficulties with pH treated in a similar way necessitated statements 17 and 27 in Tables 2 and 3. These misconceptions about pH persisted despite extensive student practical experience; so it could be due to the difficulty students have in simultaneously relating the microscopic ionisation of water, the symbolic definition of pH and their macroscopic observations (Nakhleh & Krajcik, 1994). The limits on human working memory make it difficult for novices to move as fluently between these representations as do experts (Johnstone, 1999).



Description of Student Difficulty	Propositional Knowledge Statements
pH 10 is acidic (Linke & Venz, 1979) pH is a measure of acidity of a substance (Cros et al., 1986) .pH measures level of acidity *(Ross & Munby, 1991)* pH is a measure of acidity but not basicity (Garnett et al., 1995)	Acidic solutions have a pH < 7. Basic solutions have a pH > 7 (Nakhleh & Krajcik, 1994; IUPAC, 1997)
Description: pH is only a measure of acidity	(Separate statements) Acidic solutions have a pH < 7 Basic solutions have a pH > 7
pH 5 is basic (Linke & Venz, 1979) *pH changes 3 to 0 when base is added to acid* (Nakhleh & Krajcik, 1994) The most acidic solution is that with the highest pH Bradley & Mosimege, 1998)	The pH scale relates to both acidity and basicity of aqueous solutions. Acidic solutions have a pH < 7 Basic solutions have a pH > 7
DESCRIPTION of DIFFICULTY The pH scale relates only to acids and not bases. It follows that increasing acidity will increase the pH of a solution.	PROPOSITIONAL STATEMENT The pH scale relates to both acidity and basicity of aqueous solutions. Acidic solutions have a pH < 7. Lowest values indicate the most acidic solutions. Basic solutions have a pH > 7. Highest values indicate the most basic solutions. Neutral solutions have a pH of 7.

Figure 1: Illustration of the Reciprocal Matching and Honing Process used to clarify descriptions of student difficulties and propositional statements

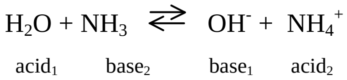
The importance of propositional statements in resolving anomalies in descriptions of student difficulties

Some statements of “misconceptions” that were reported in the literature appeared anomalous. These are shown in Table 4 together with our suggested statements

Table 4. *Reported “Misconceptions” and Corresponding Propositional Knowledge Statements*

Description of Student Difficulty	Reference	Suggested Propositional Statements
Acid and base react to give a salt	(Wilson, 1998)	6, 13 and 19
Bases do not react with acids to produce salts	(Bradley & Mosimege, 1998)	6, 13 and 19

On matching these reported “misconceptions” with their corresponding propositional statements we immediately noticed an apparent contradiction posed by the two descriptions. The studies reported neither clear propositional statements nor the acid-base model they expected students to use. In order to try and resolve the anomaly we applied the Brønsted-Lowry model to the reaction scheme in Figure 2.



$$\underset{\text{acid}_1}{H_2O} + \underset{\text{base}_2}{NH_3} \rightleftarrows \underset{\text{base}_1}{OH^-} + \underset{\text{acid}_2}{NH_4^+}$$

Figure 2: Typical Acid-Base reaction in Brønsted-Lowry Model – Symbolic Context

If Wilson’s student was using macroscopic representations applied to strong acids and bases (Statement 6) then Wilson (1998) correctly judged this as an alternative conception, providing she had the Brønsted-Lowry scheme in mind. However, if the student were using the IUPAC definition of a salt given in Statement 19 there would be no alternative conception as the product in Figure 2 is undoubtedly an assembly of anions and cations. On the other hand, Bradley and Mosimege (1998) appear to expect their students to use a macroscopic representation applied to strong acids and bases (Statement 6). Their student appears to use the Brønsted-Lowry reaction scheme competently. Without a carefully constructed, and explicitly stated, set of propositional statements against which to judge a suspected alternative conception, little useful data on student difficulties is evident. At least six other instances of such anomalies were encountered, indicating that researchers need to make the model and representation system that they have in mind clearly overt.

CONCLUSIONS

The importance of an explicit and carefully formulated set of propositional knowledge statements for high school acid-base chemistry has been shown. Using a reciprocal matching process, we have shown that student difficulties can be used to clarify propositional statements. At the same time such statements can also help identify and clarify descriptions of students’ alternative conceptions from the literature, as well as challenge some of those already published. When describing their framework to classify student difficulties, Grayson et al. (2001)

emphasised the importance of multi-contextual evidence for synthesising a “stable description” of the difficulty. The results of the present study suggest that such an accurate description of a particular difficulty should also be based on, and can be honed by, an accurate propositional statement giving the corresponding conceptual knowledge that students should have. This is in line with the call by Garnett et al. (1995) for the use of propositional knowledge statements to promote greater rigor in such studies. Our results also show that studying student misconceptions can also lead to more comprehensive, overt statements of the student knowledge expected. Thus, propositional statements could be used as a foundation for curriculum and textbook design. Furthermore, effective teaching could start with ensuring students have explicit knowledge of the appropriate model which they can apply to explain phenomena. Such a strategy was proven effective by Hand and Treagust (1998) in the simpler concepts of this topic. Future studies will entail formulation of a comprehensive description of student difficulties in acid-base chemistry to facilitate design of appropriate teaching strategies. Further clarification of the wording of these propositional statements may be needed as other student difficulties are studied. The difficulties encountered in preparing these statements so they cover the topic adequately, yet do not introduce a hybrid model, show that textbooks may not be the best reference. In this regard, we believe that a formal content analysis of the acid-base chapter of a range of textbooks would verify this opinion.

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REFERENCES

Andersson, B. (1990) Pupils' conceptions of matter and its transformations (age12-16) *Studies in Science Education 18* 53-85

Barker, V. (2001) *Beyond Appearances: Students’ misconceptions about basic chemistry.* Retrieved March 30, 2001 from Royal Society of Chemists Website: www.chemsoc.org/network/learnet/miscon.htm

Bell, R.P. (1969) Acids and Bases (2nd ed). Methuen, London

Bradley, J. D. & Mosimege, M. D. (1998) Misconceptions in acids and bases: a comparative study of student teachers with different chemistry backgrounds. *South African Journal of Chemistry 51(3)* 137-145

Brønsted, J. N. (1926) The Acid-base function of molecules and its dependency on the electric charge type. *Journal of Physical Chemistry 30* 777-790

Brønsted, J. N. & Guggenheim, E. A. (1927) Contribution of the theory of acid and base catalysis. The mutarotation of glucose. *Journal of the American Chemical Society 49* 2554-2560

Carr, M. (1984) Model confusion in chemistry. *Research in Science Education 14* 97-103

Cros, D., Maurin, M., Amouroux, R., Chastrette, M. and Leber, J. (1986) Conceptions of First year University Students of the Constituents of matter and notions of acids and bases. *European Journal of Science Education 8*(3) 305 – 313

de Vos, W. & Pilot, A. (2001) Acids and bases in layers: The stratal structure of an ancient topic. *Journal of Chemical Education, 78*(4) 494-499

de Vos W. & Verdonk, A. H. (1996) The particulate nature of matter in science education and science. *Journal of Research in Science Teaching 33*(6) 657-664

Garnett, P. J., Garnett, P. J. & Hackling, M. W. (1995) Student’s alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education 25* 69-95

Grayson, D. J., Anderson, T. R. & Crossley, L. G. (2001) A four-level framework for identifying and classifying student conceptual and reasoning difficulties. *International Journal of Science Education 23(*6) 611-622

Halstead, S. E., Anderson, T. R. & Spankie, S. (2002) Student difficulties with different models in acid-base chemistry. In Malcolm, C. & Lubisi, C. (eds) *Proceedings of the 10th Annual Conference of the Southern African Association for Research in Mathematics, Science and Technology Education*. Durban

Hand, B. M. & Treagust, D. F. (1988) Application of a conceptual conflict teaching strategy to enhance student learning of acids and bases. *Research in Science Education 18* 53-63

IEB (1997) *Senior Certificate Examination Resource Material for Physical Science A Guide to the Senior Certificate Syllabus (HG and SG).* Independent Examinations Board, Randburg, South Africa

IUPAC (1997) *Compendium of Chemical Terminology 2nd Edition* (Electronic version) retrieved December 2nd, 2002 from http://www.iupac.org/goldbook/

Johnstone, A. H. (1999) The nature of chemistry. *Education in Chemistry 36(2)* 45-47

Justi, R. S. & Gilbert, J. K. (1999) A cause of ahistorical teaching: Use of hybrid models. *Science Education 83* 163-177

Linke, R. D. & Venz, M. L. (1979) Misconceptions in physical science among non-science background students: II. *Research in Science Education 9* 103-109

Lowry, T. M. (1923) The uniqueness of hydrogen *Chemistry and Industry (42)* 43-47

Nakhleh, M. & Krajcik, J..S. (1994) Influence of levels of information as presented by different technologies on student understanding of acid-base and pH concepts. *Journal of Research in Science Teaching* 31 1077-1096

Ross, B. & Munby, H. (1991) Concept mapping and misconceptions: a study of high-school students' understanding of acids and bases. *International Journal of Research in Science Education, 13*, 11-23

Sanger, M. J. (2000) Using particulate drawings to determine and improve students' conceptions of pure substances and mixtures. *Journal of Chemical Education 77*(6) 762-766

Selley, N. J..(2000) Students' spontaneous use of a particulate model for dissolution. *Research in Science Education 30(4),* 389-402

Schmidt, H.-J. (1991) A label as a hidden persuader: chemist's neutralisation concept. *International Journal of Science Education 13(4)* 459-471

Schmidt, H.-J. (1995) Applying the concept of conjugation to the Brønsted theory of acid – base reactions by senior high school students from Germany. *International Journal of Science Education* 17 (6) 733-741

Schmidt, H.-J. (1997) Student Misconceptions – Looking for a pattern. *Science Education 81(2)* 123-135

Wilson, J. M. (1998) Differences in knowledge networks about acids and bases of Year-12, Undergraduate and postgraduate chemistry students. *Research in Science Education 28(4)*, 429-446

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What can we learn from studies on students' conceptual difficulties? The case of propositional knowledge of acid-base models

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Acid-base models taught in school generally include an operational model, concerning macroscopic properties of substances, and more theoretical Arrhenius and Brønsted models. The present study addresses two research questions: (i) What difficulties do students experience with acid-base models? (ii) What does knowledge of such difficulties tell us about what we should be teaching students about acid-base models? To identify acid-base difficulties, a review of the literature was performed and the method of Halstead *et al.* (2003) employed to synthesise difficulty descriptions through reciprocal mapping to propositional statements of acceptable scientific knowledge. Descriptions were classified on the 4-level framework of Grayson *et al.* (2001), in order to evaluate the rigor of the research process which identified each difficulty. Results showed that students create hybrid models or apply only one model to all situations, which affects their choice of examples and recognition of formulae. The process made explicit propositional knowledge of acid-base models that students may have missed, such as definitions of acids and bases to distinguish between models, together with appropriate examples to include in the curriculum. Further research is needed to clarify certain student conceptions while the research focus should change from those which have been thoroughly established to those requiring further clarification.

Introduction and theoretical framework

The human constructivist view of learning advances the idea that students need to actively construct knowledge, that this knowledge will be idiosyncratic as each person comes with different prior knowledge and experience, and that this knowledge is socially mediated (Novak, 2002). Scientific knowledge is mediated through peer-review, and this consensually accepted understanding is what formal instruction seeks to share (Millar, 1989). However, scientific knowledge is not static, as different paradigms and models have been put forward to describe and explain phenomena (Kuhn, 1970).

Three historical models of acid-base are usually taught in secondary school, and a further one commonly encountered in tertiary studies. These are summarised in Table 1 below which is based on Kolb (1978) and Oversby (2000).

Table 1: A summary of acid-base models

10.9 MODEL	**Operational**	**Arrhenius**	**Brønsted**	**Lewis**
Used from	Junior secondary	Junior/ senior secondary	Senior secondary	Tertiary
Focus	Substances	Substances	Molecular or ionic species	Bond formation

Acid	Contains replaceable hydrogen eg HCl	Supplier of H^+ ions in water eg HCl	Proton donor eg HCl, NH_4^+	Electron pair acceptor eg $AlCl_3$
Base	Neutralizes acids eg NaOH	Supplier of OH^- ions in water. eg NaOH	Proton acceptor eg NH_3, OH^- ion	Electron pair donor eg Cl^-
Acid-base reaction	Neutralization	Neutralization	Any proton transfer	Co-ordinate bond formation
General equation	Acid + base → salt + water	$H^+ + OH^- \rightarrow H_20$	HA + B → BH +A	A + :B → A:B
Limitations	Only descriptive	Substances in aqueous solutions	Proton transfer reactions only	Generalized theory

The operational model is usually the first model that students encounter. It describes acids and bases in terms of macroscopic properties displayed by classes of substances or their solutions (Oversby, 2000). Later they might encounter the Arrhenius model (1903; 1912) wherein acids or bases all undergo the same neutralization reaction between hydrogen ions and hydroxide ions to produce water. More senior students will need to accommodate the Brønsted model, which allows a broader concept of a base, accommodating species with no hydroxide group. More fundamentally, this model focuses on molecular or ionic species rather than the substances and is not limited to neutralization (Brønsted, 1926). During tertiary studies, students will need the Lewis model to explain complex formation (Kolb, 1978). While students should accommodate different conceptions of acids and bases as they mature, more advanced models should not supplant others learned earlier; each has applicability in particular contexts.

Extensive research has shown that students can have difficulties with models (e.g. Justi & Gilbert, 1999) including with acid-base models (e.g. Drechsler & Schmidt, 2005a; 2005b; Kousathana *et al*., 2005). However, few such papers have considered the specific knowledge students need in order to use the different models effectively. In this regard, the present study aims to reveal missing or unacceptable parts of students' propositional hierarchy (Novak & Gowan, 1984) needed to promote student understanding of models. Propositional knowledge involves the connections between concepts; the proposition lies in the meaning, rather than the exact words (Novak *et al.*, 2002). The present study also aims to address the paucity of reviews and syntheses that have been published concerning student difficulties with acid-base chemistry. Despite repeated calls for reviews of research into student conceptions (e.g. Nussbaum, 1998; Erickson, 2000), there has been a dearth of such reviews (Tsai & Wen, 2005), especially within acid-base chemistry.

In this study we addressed the following research questions:

1. What difficulties do students experience with acid-base models?
2. What does knowledge of such difficulties tell us about what we should be teaching students about acid-base models?

Method

To the authors' knowledge there was no suitable method for synthesizing descriptions of student difficulties from separate research studies, so we derived our own. The approach of Torgerson (2003) was used to perform a comprehensive review of a wide range of literature sources, including various smaller studies not published in the main academic journals. We extracted three types of information from the publications. This included, firstly, contextual information on the student population in the study and details of the methods used for investigating their conceptions. Then our main data comprised relevant student quotations and authors' descriptions of their difficulties. This was limited to studies conducted after instruction in the particular model. Finally, where published, related propositional knowledge was extracted. The method of Halstead *et al.* (2003) was then employed to synthesise difficulty descriptions, through reciprocal mapping to propositional statements of acceptable scientific knowledge as illustrated in Figure 1 below.

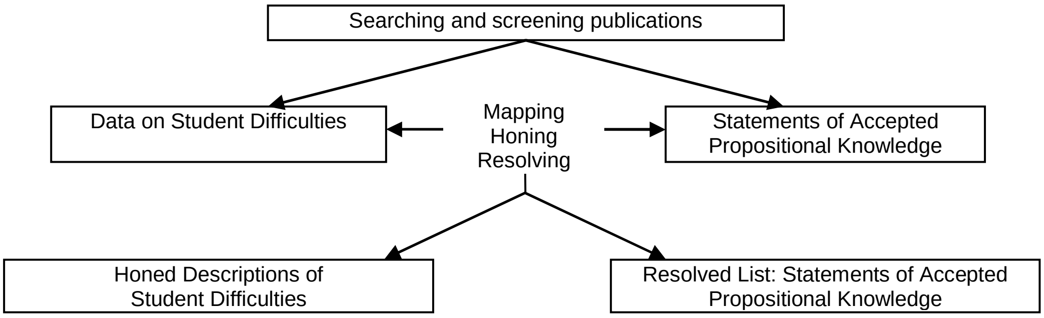

Figure 1. Overview of the research process used to hone difficulty descriptions (based on Halstead *et al*., 2003)

In this method, the data on student difficulties were first mapped to suitable statements of propositional knowledge. Then, not only did these statements allow easy sorting of the data into categories, but also clarified the essence of the difficulty in that frequently, it was only necessary to reverse the propositional statement(s). The process also illuminated the propositional knowledge that students might have absorbed inappropriately or not at all; sometimes we had to find or clarify statements to specifically address the difficulty. If these were not available from the original research reports, other chemistry and chemistry education sources were consulted. This two-way process then simultaneously honed descriptions of difficulties and made overt the corresponding propositional knowledge. We do not claim that the propositional knowledge concerned is a comprehensive list of all that students should know (as in a curriculum statement), but rather, it indicates potentially "troublesome knowledge" (Perkins, 1999).

In order to evaluate the quality of the original research on which difficulty descriptions were based, each description was classified on a 4-level framework modified from Grayson *et al.* (2001). No individual report showed sufficient rigor to allow classification at level 4, but data reported from several studies allowed a more comprehensive 'picture' of a student's conception to be obtained (Marin *et al.*, 2004) so that the level 4 (Table 1) requirement of triangulation could be upheld (See Table 2).

Table 2: A 4-Level framework of criteria for classifying descriptions of student difficulties (modified from Grayson *et al.*, 2001).

1	Suspected	Intuitive or subjective description	Teaching experience/ anecdotal OR Unanticipated data or uncontrolled data, e.g. unvalidated MCQ
2	Emergent	Description based on research, may vary between contexts	Some controlled research No triangulation reported
3*	Partially established	More explicit description, open to modification	At least one triangulated study OR identified separately in several independent studies
4	Established	Description is stable – it does not vary between contexts	Triangulated studies in multiple contexts

*Level 3+ indicates that more than one context was studied but with insufficient rigor for Level 4.

Results

The scope of the studies

The literature search revealed fourteen suitable publications. These are indicated with * in the list of references. All authors reported at least one open-ended source of data collection (interviews or pencil and paper). Drechsler and Schmidt (2005a; 2005b) used only interviews while all the other authors included a second source of data – some being multiple-choice items. Nine reports gave data collected in Europe; two came from Australia, and one each from Canada, Tunisia and India. This was judged to represent a wide variety of educational contexts, with many language groups. Cros *et al.* (1986) worked among first year university students in France. Toplis (1998) collected data from junior secondary students in the United Kingdom. The remaining studies were all conducted among senior secondary students who had chosen some chemistry specialization, corresponding to Grades 10 to 12 in South Africa. Drechsler and Schmidt (2005b) include some data from teachers. Since none of the studies included the Lewis model, it was decided to limit the study to conceptions within an operational model and the Arrhenius and Brønsted theoretical models as taught in secondary school.

Results on student difficulties with models

Table 3 shows six difficulties with their classification on the 4-level framework (Grayson *et al.*, 2001) and the corresponding propositional statements. In this section we highlight the reasoning used to reciprocally match the various difficulties with propositional knowledge.

Table 3: A summary of student difficulties with corresponding propositional knowledge

		Level
1	**Definitions of acids and bases are limited to operational definitions in terms of the properties of their solutions** In aqueous solution, acidic and basic substances display characteristic properties Acidic and basic substances dissolve in water to give acidic and basic solutions Acidic solutions taste sour, react with carbonates and have a pH less than 7 Basic solutions have a pH greater than 7 Operational definitions indicate how a physical quantity might be recognised or measured Theoretical definitions show how the concept relates to other concepts	4
2	**Acids and bases are substances not particles** Brønsted acids can release H+ and Brønsted bases can accept H+ (Interim, see below) Acids and bases can be conceived as substances or as particles according to different models. Brønsted acids are molecules or ions that can release a proton (hydrogen ion) Brønsted bases are molecules or ions that can accept a proton (hydrogen ion)	4
3	**Acid and base definitions are not distinguished** Arrhenius acids are substances that release hydrogen ions when dissolved in water Arrhenius bases are substances that release hydroxide ions when dissolved in water	2
4	**Examples of acids and bases are limited to the Arrhenius model** Arrhenius bases all contain OH groups, such as NaOH Brønsted bases include NH_3, CH_3COO^-,CN^-, and S^{2-} Brønsted acids include H_2O, HCO_3^-, HS^-, and NH_4^+ (See difficulty 5) Brønsted acids include the water molecule Arrhenius acids do not include water Brønsted bases include OH^- Brønsted bases do not include NaOH	4
5	**Alkali is another word for base** Alkali is an alternative term for Arrhenius bases Arrhenius acid and bases do not include water Brønsted bases include the water molecule (see Difficulty 4)	2
6	**The general Brønsted reaction scheme shows neutralization** The general Brønsted reaction scheme does not apply to particular substances in neutralization In the Brønsted model, neutralization is shown as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$	3^+

Difficulties concerning the definitions of acids and bases

Three difficulties with acid-base definitions have been shown by the analysis.

Difficulty 1: Definitions of acids and bases are limited to operational definitions in terms of the properties of their solutions

The conception: "acid means sour" reported by Toplis (1998) was probably acceptable among junior secondary students in the United Kingdom. But senior students in Sweden continued to confuse the concepts sour, acid, and acidic substance as well as basic and base and basic substance (Drechsler & Schmidt, 2005b). From interviews with Australian Grade 10 students, Hand and Treagust (1988) identified the conception: "An acid is something which eats material away or which can burn you". Even at university, students did not distinguish between substances and their solutions, using only an operational model as they gave "purely descriptive definitions of acids and bases" such as $pH < 7$ or $pH > 7$ (Cros *et al*., 1986). These difficulties were mapped to the following propositional knowledge statements (See also Table 3), distinguishing the solutions from the substances or ions in solution:

In aqueous solution, acidic and basic substances display characteristic properties.

The converse of this propositional knowledge highlights the commonalities between the reports. It suggested the following description of the student difficulty:

Properties of acidic or basic solutions give a definition for acids or bases.

The mapping process was then continued from the original data, suggesting further propositional knowledge distinguishing substances from solutions, which needs to be made explicit to students.

Acidic and basic substances dissolve in water to give acidic and basic solutions.

Acidic solutions taste sour, react with carbonates and have a pH less than 7.

Basic solutions have a pH greater than 7.

Finally, we examined the difficulty in relation to the types of definitions in science (Galili & Lehavi, 2006). Accordingly, the difficulty mapped to further propositional knowledge:

Operational definitions indicate how a physical quantity might be recognised or measured.

Theoretical definitions show how the concept relates to other concepts

Consequently, the difficulty description could be honed even further: *Definitions of acids and bases are limited to operational definitions in terms of the properties of their solutions.* This difficulty could be classified as Established at Level 4 because it has been found in four contexts and the same description applies in the different contexts. Thus no further research into the nature of this difficulty is warranted. The focus could change to investigate why the older students have not integrated a theoretical definition.

Difficulty 2: Acids and bases are substances not particles

Students prefer using, and are more familiar with, Arrhenius' definitions and explanations than with Brønsted's (Cros *et al*., 1986; Drechsler & Schmidt, 2005b; Demerouti *et al*., 2004). Kousathana *et al*. (2005) found that students tended to justify their choice of species by referring to the Arrhenius model, even when asked which species "is not a Brønsted-Lowry acid". These results mapped to a propositional statement giving simple Brønsted definitions. *Brønsted acids can release* H^+ *and Brønsted bases can accept* H^+. From this we derived an interim description of the difficulty: *Students limit their conception of acids and bases to the Arrhenius model.*

Later research offers clarification. Grade 11 students in Germany "considered acids as substances and not as particles" (Sumfleth, 1987). Similarly, Swedish teachers "gave definitions of acids in terms of substances" (Drechsler & Schmidt, 2005b). Carr (1984) advocates making the necessary knowledge explicit, so a further propositional statement was needed, specifically:

Acids and bases can be conceived as substances or as particles according to different models.

Finally, inverting this propositional statement allowed the difficulty description suggested by Sumfleth to be honed to *Acids and bases are substances not particles* which highlights the difficulty students have with accommodating the newer and more abstract Brønsted model. The description appears to be stable across these multiple contexts and we considered it Established at Level 4.

In mapping the description of the difficulty back to the propositional knowledge of the definition, we saw the inadequacy of the definitions given earlier which do not clarify the fundamental differences between Brønsted's and earlier models. The propositional statements are based on IUPAC (2007) definitions:

Brønsted acids are molecules or ions that can release a proton (hydrogen ion).

Brønsted bases are molecules or ions that can accept a proton (hydrogen ion).

The reciprocal mapping between difficulties and propositional knowledge was used twice in this case: firstly to sharpen the description of the difficulty and then to make the definition (propositional knowledge) more explicit.

Difficulty 3: Acid and base definitions are not distinguished

Students sometimes interchange definitions of acids and bases (Linke & Venz, 1979; Vidyapati & Seetharamappa, 1995) or give the same definitions for both (Linke & Venz, 1979). Two further studies show students' confusion, for example thinking OH^{-} ions were found in acids (Ross & Munby, 1991) or among juniors: "acids can be alkaline or neutral" (Toplis, 1998). These might simply be mistakes, which are easily corrected (Abimbola, 1988), rather than genuine conceptual difficulties, however, further research suggests otherwise. Ouertatani *et al.* (2007) classified students' responses for acids: "acceptor of hydrogen ions" and "donor of hydroxide ions" (10% each) and for bases: "acceptor of hydroxide ions" (20%). These incidences suggest a non-trivial difficulty of confusion between models, which needs further investigation. Thus we only classify the difficulty as Emergent or Level 2 because the description is still exceptionally vague, not indicating the essence at all, despite being reported in three contexts. Further research should probe which conceptual links are missing or inappropriate for these students and further illuminate the propositional knowledge that students do not appear to have. At present, we simply include Arrhenius definitions to add to the Brønsted definitions given in difficulty 2.

Arrhenius acids are substances that release hydrogen ions when dissolved in water.

Arrhenius bases are substances that release hydroxide ions when dissolved in water.

Difficulties with examples of acids, bases and salts

Research has shown that students have access to a limited number of and inappropriate examples for acids and bases.

Difficulty 4: Examples of Acids and Bases are limited to the Arrhenius model

University students mentioned ethanoic acid twice as often as they mentioned its conjugate base, ethanoate ion, CH_3COO^{-} (Cros *et al.*, 1986). Students frequently did not accept as bases examples without OH^{-} ions (Schmidt & Volke, 2003; Ouertatani *et al.*, 2007). Specific bases not recognised include NH_3 (Kousathana *et al.*, 2005; Furió-Más *et al.*, 2007), CN^{-} (Kousathana *et al.*, 2005) and S^{2-} (Furió-Más *et al.*, 2007) which are all Brønsted bases but not Arrhenius bases. Brønsted acids that were not Arrhenius acids were also not recognized, for example

NH_4^+, H_2O, HS^- and HCO_3^- (Kousathana *et al.*, 2005).

In these studies, despite having already encountered the Brønsted model, students only recognised Arrhenius examples. The source could lie in their instruction, as suggested by Drechsler and Schmidt (2005b) who found the difficulty of similarly circumscribed examples among Swedish teachers. In this regard, Herron (1996) emphasises using examples beyond the typical prototypes to show the scope of the concept. Consequently, in this particular case, we concluded that the greater scope of the Brønsted model needed examples including water and ions. Accordingly, the troublesome chemical species above are included as propositional knowledge in the following statements:

Arrhenius bases all have OH groups, such as NaOH.

Brønsted bases include NH_3, CH_3COO^-, CN^-, *and* S^{2-}.

Brønsted acids include H_2O, HCO_3^-, HS^-, *and* NH_4^+.

The above statements of missing propositional knowledge show that students have limited exposure to Brønsted acids and bases so the difficulty can be described as: *Examples of acids and bases are limited to the Arrhenius model.* The description is stable across the multiple contexts in which it is found, thus enabling a classification of Level 4 or Established and suggesting that no further research is necessary regarding the nature of the difficulty.

Two examples of student difficulties that need special attention pertain to water and sodium hydroxide. Water as a Brønsted acid or base presents particular difficulties for students. For example, Kousathana *et al*. (2005) and Drechsler and Schmidt (2005a) both report that students avoided options where water was described as an acid (or acted as a proton donor) or was described as a base (or acted as a proton acceptor). In an interview on this, a student commented: “I can't imagine drinking an acid but you drink water” (Drechsler & Schmidt, 2005b). The student’s words suggest that it is their familiarity with water that creates the problem, but there is a lack of controlled research data on this particular aspect. As Carr (1984) emphasises, students need to become explicitly aware of the differences between models. Furthermore, Herron (1996) emphasises the importance of non-examples to indicate the boundary of a concept. Accordingly, we put forward the following propositional statements specifically about water:

Brønsted acids include the water molecule, H_2O.

Brønsted bases include the water molecule, H_2O.

Arrhenius acids do not include water.

Problems with sodium hydroxide, reported by Drechsler and Schmidt (2005b), give the example of a student who describes an acid-base reaction as, “HCl is an acid and NaOH is a base”, and then continues by saying, “I think that a proton is transferred from the acid to the base.” Again, there is little controlled research on students’ applying the Brønsted proton transfer model to substances. However, content analysis of textbooks (e.g. Drechsler & Schmidt, 2005a; Furió-Más *et al*. 2007) shows that many do confuse models of bases, in particular using NaOH instead of OH^- for a Brønsted base. Consequently, we derived the following two propositional statements to show the distinction; NaOH was already included above as an Arrhenius base.

Brønsted bases include hydroxide ion, OH^-.

Brønsted bases do not include NaOH.

Difficulty 5: Alkali is another word for base

Toplis (1998) reported the conception: “Alkali means cancels or neutralizes acid” which is probably acceptable among the reported 13% of the junior secondary students. However, the conception persists later. In reply to a question that required students to apply the Brønsted model, a senior student interviewed in Schmidt and Volke’s (2003) study responded: “Water as an alkali is difficult to conceive”. These authors clarify that the term *alkali* relates to substances and consequently has no place in the Brønsted model, but when students consider the words base and alkali to be completely interchangeable, they are mixing models. Toplis (1998) reported only limited details while Schmidt and Volke did not generalise beyond one student. Consequently, this difficulty is therefore classified as Emergent or Level 2. Appropriate examples and non-examples are given to clarify the two theoretical models for bases. This difficulty then maps to the following propositional statements, which go beyond an explanation of terms.

Arrhenius model: alkali is an alternative term for bases.

Arrhenius bases do not include water.

Brønsted bases include the water molecule.

Difficulties with mixed models

Difficulty 9: The general Brønsted reaction scheme shows neutralization

In the introduction, the three different ways in which the acid-base models describe a neutralisation reaction were shown. These can be summarised by the equations in Figure 2.

acid + base $\rightarrow$ salt + water	(1) operational
$H^+ + OH^- \rightleftharpoons H_2O$	(2) Arrhenius
acid $\rightarrow$ base + H^+	(3) Brønsted scheme
$\text{acid}_1 + \text{base}_2 \rightleftharpoons \text{base}_1 + \text{acid}_2$	(4) Brønsted general reaction
$H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$	(5) Brønsted neutralization

Figure 2. Typical equations for acid-base reactions in different models

Two research reports suggest the idea that students may superimpose one acid-base model on another, imagining that they describe the same ideas. Firstly, Hand and Treagust (1988) report the following misconception among Grade 10 students in Australia: “Neutralisation is the breakdown of an acid or something changing from an acid”. Such a student could have Brønsted’s reaction scheme in mind – thinking that equation (3) in Figure 2 depicted an acid breaking down and that this was neutralization. Then Ross and Munby (1991) report a conception on a Canadian student’s concept map: a base is the product of neutralization. Such a student could imagine that either equations (3) or (4) for the Brønsted model showed neutralization. Both statements suggest that students are inappropriately superimposing the general reaction scheme of the Brønsted model onto a neutralization reaction. Thus these students should have rather applied equations (1), (2) or (5) to neutralization.

Drechsler and Schmidt (2005b) give qualitative data from interviews showing that students believed that the operational equation (1) and a Brønsted representation (4) both contained the same information. Indeed, both do have acid + base as reactants, which could create confusion for students, especially if they do not distinguish the acid-base models. For example, when confronted with the two equations, a student concluded that “salt and water are formed... there should be an acid and a base as well...perhaps you can identify NaCl as an acid...” These authors categorize this difficulty as being due to students not understanding the appropriate contexts for each model. Consequently, we mapped this difficulty to the following propositional knowledge statements making this difference overt.

The general Brønsted reaction scheme does not apply to particular substances in neutralization.

In the Brønsted model, neutralization is shown as: $H_3O^+ + OH^- \rightleftharpoons H_2O + H_2O$

Reversing these propositional statements led to the difficulty description: T*he general Brønsted reaction scheme shows neutralization.* This difficulty is partially established through one triangulated study and suggested in two other contexts, thus is classified at level 3+. Further confirmation is needed through studies in other chemical contexts and among other student populations.

Conclusions

The outcomes of this research are two-fold. Firstly, they show some of the difficulties that students experience in moving between several acid-base models. Secondly, the research has also made overt some of the missing propositional knowledge that can result in these difficulties.

Models for acids and bases create many difficulties for students. This synthesis indicates students deal with the various acid-base models in three different ways. Firstly, they do not accommodate new models, simply falling back on the one learned first, as Hawkes (1992) has already noted. This was evident in Difficulties 1, 2 and 4 where students limited their definitions or examples to particular models. They might use the operational rather than a theoretical model or retain only Arrhenius conceptions while ignoring Brønsted concepts. Furthermore, this was also evident among teachers whose examples of bases were limited to those containing OH groups. The students' second strategy manifests when they consider earlier models as irrelevant, using only the latest one taught. This is shown in Difficulty 6 where students apply the Brønsted model to neutralisation reactions between substances, whereas an operational model would be more appropriate. Carr (1984) emphasises that students need clear 'signposts' to show where one model is more applicable than another. In particular, particles rather than substances are implicit in the Brønsted model, but this tacit knowledge of experts is seldom explicit for students. Thirdly, students might create a hybrid model, incorporating aspects of each model into a personal mixture of ideas, as was evident in Difficulties 3, 4, 5 and 6. Here, students amalgamated definitions from two models with consequent confusion, or they used sodium hydroxide rather than the hydroxide ion as a Brønsted base and they absorbed the term alkali from the operational and Arrhenius models into the Brønsted model.

In essence, the strategies that students adopt with multiple models suggest they conceive models as 'one size fits all', with a single model applicable across all contexts. This problem occurs more widely than in the acid-base context, and infers that students do not understand the nature of science (Justi & Gilbert, 1999; Justi, 2000). In an analysis of students' conceptions in chemistry, Talanquer (2006) concluded that 'commonsense learners' believe in a one-to-one correspondence between models and reality. These students would accommodate only one model, as has been confirmed here in the acid-base context.

This analysis of student difficulties has also exposed some of the propositional knowledge that could be missing or inappropriately held by students (Novak & Gowan, 1984; Novak, 2002). Experts know which model to use in each situation, they know the limitations of each model, they move fluently between them according to the demands of the situation (Johnstone, 1982). Much of this propositional knowledge seems obvious to experts as it is part of their tacit knowledge, and this is mirrored in their teaching (Loeffler (1989). In contrast, students lack this knowledge and need it to be made explicit for them. How this should be made explicit is not part of this research. Rollnick *et al.* (2008) found that expert teachers with good subject matter knowledge could articulate the nuances of a topic, making it more accessible for students. This also confirms Carr's (1984) view that student difficulties are "more usually perceived in terms of confusion about models used in teaching the concept than as a conflict between preconceptions and the scientific view". Consequently students need specific instruction about the models; we cannot rely on them to develop them intuitively. Research involving content analyses of textbooks has shown similar confusion and lack of explicit differentiation between models; for example: Evans and Lewis (1998), de Vos and Pilot (2001), Drechsler and Schmidt (2005a). Furthermore, Schmidt (1995) contends that textbook authors ignore certain misconceptions, yet teachers needed to become aware of these misconceptions if they were to address them. In the same way Gabel (1999) observed that the changes in chemistry textbooks since the 1950's had "not been driven to any great extent by research findings". Seemingly, teachers' main source of reference (Costa *et al.*, 2000) has not been highlighting the research on student conceptions.

Discussion

Limitations of the research

This research has limitations because it is a secondary interpretation of student responses. However, all data from the reports were considered in the context of the original research and our descriptions appeared to be consistent with the authors' interpretations. A further limitation is the lack of rigor shown in some of the original research. The 4-level framework in Table 2 allowed us to evaluate the quality of the research. For example Toplis (1998) (see Difficulty 5) does not report sufficient qualitative data to warrant classifying the description of the difficulty beyond emergent or Level 2. Furthermore, 4 of the 14 research reports analysed here gave no indication of the propositional knowledge they considered scientifically acceptable, almost half of the reports gave general conceptual background with some specific statements pertaining to their probes. Not one gave an explicit list of propositional knowledge statements against which they identified difficulties as recommended by Treagust (1988).

Implications for further research

This synthesis shows that some difficulties with acid-base models have been inadequately researched. In particular, we know very little about students' interchanging definitions (Difficulty 3), nor whether *alkali* is indeed used interchangeably with *Brønsted base* (Difficulty 5). We also need to confirm the use of the Brønsted general reaction equation for neutralization (Difficulty 6) in more chemical and educational contexts. Descriptions of difficulties 1, 2 and 4 are all classified as Established. Further research into their nature would be redundant; another focus is needed. For example, the place of the Brønsted model in the curriculum should be investigated. Is it too abstract for most school students as Herron (1975) argues? There is little evidence that students aged less than 17 years work comfortably and fluently with sub-microscopic chemical conceptions (Gabel, 1993; Brosnan & Reynolds, 2001) and a cross-age study such as that carried out by Brosnan and Reynolds (2001) would be useful in the context of acid-base models.

References

Abimbola, I. O. (1988). The problem of terminology in the study of students' conceptions in science. *Science Education*, 72(2), 175-84.

Arrhenius, S. (1903). Development of the theory of electrolytic dissociation. *Nobel lecture December 11, 1903*. http://www.nobel.se/chemistry/laureates/1903/press.html [Retrieved 21st November 2002]

Arrhenius, S. (1912). Electrolytic Dissociation. *Journal of the American Chemical Society*. 34(4) 353-364

Brønsted, J. N. (1926). The acid-base function of molecules and its dependency on the electric charge type. *Journal of Physical Chemistry*, 30, 777-790.

Brosnan, T. & Reynolds, Y. (2001). Students' explanation of scientific phenomena: Macro and micro differences. *Research in Science and Technology Education*, 19(1), 69-78.

Carr, M. (1984). Model confusion in chemistry. *Research in Science Education*, 14, 97-103.

Costa, N., Marques, L. & Kempa, R. (2000). Science teachers' awareness of findings from educational research. *Chemistry Education: Research and Practice*, 1(1), 31-36. http://www.uoi.gre/cerp [Retrieved 7th June 2007]

*Cros, D., Maurin, M., Amouroux, R., Chastrette, M. & Leber, J. (1986). Conceptions of first year university students of the constituents of matter and notions of acids and bases. *European Journal of Science Education,* 8(3), 305-313.

De Vos, W. & Pilot, A. (2001). Acids and bases in layers: The stratal structure of an ancient topic. *Journal of Chemical Education,* 78(4), 494-499.

*Demerouti, M., Kousathana, M. & Tsaparlis, G. (2004). Acid-base equilibria, part I: Upper secondary student's misconceptions and difficulties. *The Chemical Educator,* 9, 122-131.

*Drechsler, M. & Schmidt, H.-J. (2005a). Textbooks' and teachers' understanding of acid-base models used in chemistry teaching. *Chemical Education Research and Practice,* 6(1), 19-35 http://www.rsc.org/Education/CERP/issues/2005_1/textbooks .asp [retrieved 31st October 2002]

*Drechsler, M. & Schmidt, H.-J. (2005b). Upper secondary school students' understanding of models used in chemistry to define acids and bases. *Science Education International,* 16(1), 35-53.

Erickson, G. (2000). Research programmes and the students science learning literature. In R. Millar, J. Leach & J. Osborne (Eds.) *Improving Science Education: the contribution of research*. (pp 271-292). Open University Press, Buckingham, Philadelphia.

Evans, E. W. & Lewis, R. (1998). The teaching of basic chemistry to university foundation students. *University Chemistry Education,* 2(2), 55-57. http://www.rsc.org/uchem/uchemed/ztm [Retrieved 2nd August 2008]

*Furió-Más, C., Calatayud, M.-L. & Bárcenas, S. L. (2007). Surveying students' conceptual and procedural knowledge of acid-base behaviour. *Journal of Chemical Education,* 84(10), 1717-1724. Supplemental material from http://jchemed.chem.wisc.edu/Journal/Issues/2007/Oct/ [Retrieved 8th February 2008].

Gabel, D. (1999). Improving Teaching and learning through chemistry education research, a look to the future. *Journal of Chemical Education,* 76(4), 548-554.

Galili, I. & Lehavi, Y. (2006). Definitions of physical concepts: a study of teachers' knowledge and views. *International Journal of Science Education,* 28(14), 521-541.

Grayson, D. J., Anderson, T. R, & Crossley, L. G. (2001). A four-level framework for identifying and classifying student conceptual and reasoning difficulties. *International Journal of Science Education,* 23(6), 611-622.

Halstead, S. E., Anderson, T. R. & Spankie, S. A. A. (2003). Formulation of statements of propositional knowledge and corresponding student difficulties for the Bronsted-Lowry acid-base model: A reciprocal matching and honing process. In D. Fisher & T. Marsh (Eds.), *Proc. Third Conf. on Science, Mathematics and Technology Education* (Vol. 1, pp 377-388). East London, South Africa: Curtin University

*Hand, B. M. & Treagust, D. F. (1988). Application of conceptual conflict strategy to enhancing student learning of acids and bases. *Research in Science Education,* 18, 53-63.

Hawkes, S. J. (1992). Arrhenius confuses students. *Journal of Chemical Education,* 69(7), 542-5

Herron, J. D. (1975). Piaget for Chemists. Explaining what "good" students cannot understand. *Journal of Chemical Education,* 52(2), 146-150.

Herron, J. D. (1996). *The Chemistry Classroom.* American Chemical Society, Washington, D.C.

IUPAC (2007) Compendium of chemical terminology – the Gold book (2nd ed) http://www.iupac.org/goldbook/ [Retrieved 2nd December 2007]

Justi, R. S. & Gilbert, J. K. (1999). A cause of ahistorical teaching: Use of hybrid models. *Science Education,* 83, 163-177.

Justi, R. S. (2000). Teaching with historical models. In J. K. Gilbert & C. Boulter (Eds.) *Developing models in science education*. (pp 209-226) Dordrecht: Kluwer Academic Press.

Kolb, D. (1978). Chemical principles revisited: acids and bases. *Journal of Chemical Education,* 55(7), 459-64.

*Kousathana, M. Demerouti, M. & Tsaparlis, G. (2005). Instructional Misconceptions in Acid-Base equilibria: An analysis from a history and philosophy of science perspective. *Science and Education*, 14, 173-193.

Kuhn, T. S. (1970). *The Structure of Scientific Revolutio*ns (2nd ed). Chicago: University of Chicago Press

*Linke, R. D. & Venz, M. L. (1979). Misconceptions in physical science among non-science background students: II. *Research in Science Education,* 9, 103-109.

Loeffler, P. A. (1989). Fundamental concepts in teaching of chemistry part 1. The two worlds of the chemist make nomenclature manageable. *Journal of Chemical Education,* 66(11), 928-930.

Marín, N., Gómez, E. J. & Benarroch, A. (2004). How can we identify replies that accurately reflect students' knowledge? A methodological proposal. *International Journal of Science Education,* 26(4), 425-445.

Millar, R. (1989). Constructive criticisms. *International Journal of Science Education,* 11, 587-596.

Novak, J. D. & Gowan, D. B. (1984) *Learning how to learn*. Cambridge: Cambridge University Press.

Novak, J. D. (2002). Meaningful learning: The essential factor for conceptual change in limited or inappropriate propositional hierarchies leading to empowerment of learners. *Science Education,* 86, 548-571.

Nussbaum, J. (1998). History and philosophy of science and the preparation for constructivist teaching: the case of particle theory. In J. J. Mintzes, J. H. Wandersee & J. Novak (Eds). *Teaching science for understanding: A human constructivist view* (pp 165-194). San Diego: Academic Press.

*Ouertatani, L., Dumon, A., Trabelsi, A. & Soudani, M. (2007) Acids and bases: The appropriation of the Arrhenius model by Tunisian Grade 10 students. *International Journal of Science and Mathematics Education,* 5, 483-506.

Oversby, J. (2000). Models of Explanation in Chemistry: The case of acidity. In J. K. Gilbert & C. Boulter (Eds.) *Developing models in science education* (pp 227-232). Dordrecht: Kluwer Academic Press.

Perkins, D. (1999). The many faces of constructivism. *Educational Leadership,* 57(3), 6-11

Rollnick, M., Bennett, J. Rhemtula, M., Dharsey, N. & Ndhlovu, T. (2008). The place of subject matter knowledge in pedagogic content knowledge: A case study of South African teachers teaching about amount of substance and chemical equilibrium. *International Journal of Science Education, 30(10) 1365-1387.*

*Ross, B. & Munby, H. (1991). Concept mapping and misconceptions: a study of high-school students' understanding of acids and bases. *International Journal of Science Education,* 13(1), 11-23.

Schmidt, H.-J. (1995) Applying the concept of conjugation to the Bronsted theory of acid-base reactions by senior high school students from Germany. *International Journal of Science Education,* 17 (6) 733-741

*Schmidt, H.-J. & Volke, D. (2003). Shift of meaning and students' alternative concepts. *International Journal of Science Education,* 25(11), 1409-1424.

*Sumfleth, E. (1987). Natuurwissen-schaften im Unterricht. 35, 29-35 cited by Demerouti *et al.* (2004).

Talanquer, V. (2006). Commonsense chemistry: a model for understanding students' alternative conceptions. *Journal of Chemical Education,* 83(5), 811- 816.

*Toplis, R. (1998). Ideas about acids and alkalis. *School Science Review,* 80(291), 67-70.

Torgerson, C. (2003). *Systematic Reviews*. London: Continuum

Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education*, 10(2), 159-169

Tsai, C.-C. & Wen, M. L. (2005). Research and trends in science education from 1998 to 2002: a content analysis of publication in selected journals. *International Journal of Science Education,* 27(1), 3-14.

*Vidyapati, T. J. & Seetharamappa, J. (1995). Higher secondary school students' concepts of acids and bases. *School Science Review,* 77 (278), 82-84.

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