CHAPTER FOUR

Data processing and management

… (T) o know is, in some sense, to transform the object of knowledge.
(Bettencourt, 1993, p.39)

4.1 Introduction

In this chapter, data collected are presented and analysed. As explained in Chapter 3, the purpose of the first phase of the analysis was to elicit students' understanding of concepts in the topic of acids and bases in relation to specific practical work activities. The second phase of the analysis was to establish how students arrived at the meaning of concepts by the way they explained it (i.e. how students used their prior knowledge to construct meaning of concepts). In the third phase, a link between students' understanding of concepts and how such concepts were used in practice (mentally and practically) was established. In addition, the effect of students' prior understanding of concepts or their use would be established through analysis of data collected by observation, interviews and from students' practical reports.

To better facilitate data analysis of students' responses to questions related to these concepts, all data collected from various instruments were grouped into clusters of related and meaningful chunks of information (see exhibits). The content and quality criterion for forming clusters or chunks of information was based on propositional content knowledge statements (Appendix D) generated from the curriculum. ‘Specification knowledge’ was used as assessment criteria for the three types of knowledge individually and in their interaction during conceptualisation.

4.2 Data presentation

In this part of the report, collected data is presented and analysed within the context of students' learning environments. For better understanding of the data and the process of analysis it was important to first explain the contexts (students' previous learning environments and academic achievements) under which data was collected and analysed.

Table 8: Summary on students' profiles

ENTITY	**Case A**	**Case B**	**Case C**
Province	**Limpopo**	**Limpopo**	**Mpumalanga**
School	**SCL A** Secondary School	**SCL B** Secondary School	**SCL C** College
Year matriculated	2005	2005	2005
Matriculation results	English: **64 (HG)** Mathematics: **42 (HG)** Physical Science: **50 (HG)**	English: **38 (HG)** Mathematics: **59 (HG)** Physical Science: **47 (HG)**	English: **47 (HG)** Mathematics: **55 (SG)** Physical Science: **48 (HG)**
Research study results	**PKST** Pre-test: **49** Post-test: **43**	**PKST** Pre-test: **66** Post-test: **41**	**PKST** Pre-test: **57** Post-test: **57**
University achievement (first semester)	Chemistry: **48** Mathematics: **58** Physics: **62**	Chemistry: **56** Mathematics: **76** Physics: **72**	Chemistry: **62** Mathematics: **54** Physics: **56**
School/practical work experience/exposure (Finding applicable to all three students)	According to Kirschner and Meester (1988), "laboratory work is intrinsic to science in general and to the scientist in particular" (p. 83). Therefore, laboratory work is considered fundamental in the teaching of science. However, it also depends how one uses laboratory work in teaching. That is, the purpose of practical work should be clearly defined to achieve its goal in teaching (Hart *et al*, 2000). In their response to the level of exposure of laboratory work at school, the three students indicated that their only encounter with practical work was through teacher demonstration. This limited the students to mere observers of the reactions during chemistry experiments. For effective use of practical work, the student should be presented with problems in experimentation to challenge his or her understanding and creativity "without being so complex as to be irresolvable" (Kirschner & Meester, 1988, p. 90). It can be concluded that students' exposure to practical work was limited and could not have helped students to solve problems or to concretise theory and acquire conceptual knowledge.		

HG: Higher Grade

SG: Standard Grade

SCL: School

4.2.1 Context for data analysis

In this study, "context" refers to students' background, i.e. their academic achievements at school level and early achievements at university (see Table 8). The rationale of the context, which includes achievements in mathematics, science and language (English), refers to prior knowledge assumed to be in place when students engage in learning activities.

4.3 Data analysis

Data analysis, as indicated earlier, would have had no meaning if the context in which it was conducted was not described. The nature of this study therefore required that students' profiles include their academic backgrounds and the profiles of the schools from which they graduated. The context of how their prior knowledge was acquired and its analysis could then be better understood. In this analysis, students' profiles (as summarised in Table 8) were used as a referent in the interpretation and explanation of the data.

In the process of data analysis, information from different sources was chunked together into categories that contained the most basic knowledge required to interpret scientific concepts fully without ambiguity or without committing errors of interpretation. This information was, for the purpose of this study, labelled "presented data ". This data (see exhibits) differed from one participating student to another. This could be expected, since students have different academic backgrounds and teaching and learning experiences, hence would bring different prior knowledge into the learning situation. The analysis was conducted on the same concepts for all three students/cases. Data in exhibit boxes were sourced from all instruments (Prior knowledge state test (PKST); Observation and Interview (O&I); Practical Work Report (PWR)) used for collecting data. However, this does not mean that all sources contributed to all exhibit boxes equally for a particular student or concept.

4.3.1 Analysis: Case A (Exhibits 4.1 to 4.4)

Exhibit 4.1

Presented data

Questions, student's responses and data sources

Q.4.1.1: Differentiate between an Arrhenius and a Bronsted-Lowry acid. (PKST: Q.6)

S: Arrhenius' acids *increase the concentration of* H^+ *ions* when dissolved in *water* while Bronsted-Lowry's acids are proton donors.

Q.4.1.2: You are told that an aqueous solution is acidic. What does this mean? (PKST: Q1)

S: It means the solution has a *high concentration of* H^+ *ions.*

Q.4.1.3: As the hydrogen-ion concentration of an *aqueous solution* increases, the hydroxide-ion concentration of this solution will – (1) increase; (2) decrease; or (3) remain the same? (PKST: Q.3)

S: Decrease. (the student did not elaborate)

Q.4.1.4: When HCl (aq) is *exactly neutralised* by NaOH (aq), the hydrogen-ion concentration in the resulting solution is …

(1) Always less than the concentration of the hydroxide ions;

(2) Always greater than the concentration of the hydroxide ions;

(3) Always equal to the concentration of the hydroxide ions; or

(4) Sometimes greater and sometimes less than the concentration of the hydroxide ions. (PKST: Q.11)

S: Always equal to the concentration of the OH^- ions.

(i) Description of specification knowledge (memorandum)

As discussed earlier, the purpose of 'specification knowledge' is to reduce ambiguity in the description of concepts. Therefore, what is required should be described before any analysis can take place. In this category, the concept of interest is an "aqueous acidic" solution. Acidity is a complex concept, as it is generated from other concepts. Therefore, other concepts or terms that are related or used in one way or the other to construct the concept of acidity must be understood first to describe it.

In describing an aqueous acidic solution, the three ways in which a concept is described (specification, instantiation and error prevention) would have to be applied. That is, a student should be able to access relevant information in his or her prior knowledge base in order to construct the concept of an aqueous acidic solution. The required prior knowledge is what Reif (1985) describes as the most important knowledge to make a concept effectively usable. That is, the knowledge required to interpret the concept appropriately. That knowledge should *specify* the concept, *apply* the specification in various particular instances, and do so *without committing errors* of interpretation. With regard to the concept of acidity, the basic knowledge required to describe an aqueous acidic solution would include, but not limited to, the following:

- The specification of the relevant acid-base concept(s) to be used for the description or construction of meaning should be given (for example, an acid according to the Arrhenius concept is a substance that, when dissolved in water, increases the H^+ ion concentration in the solution).
- Different types of solutions should be understood. For this study, the student needed to understand "aqueous solution" as a solution in which water is a solvent and that an acid increases the H^+ ion concentration and a base is a substance that increases the OH^- ions when dissolved in an aqueous solution.
- It should be understood that water (H_2O) exists in equilibrium with H^+ and OH^- ions ($H_2O \rightleftarrows H^+_{(aq)} + OH^-_{(aq)}$).
- The relationship between the concentrations of H^+ and OH^- ions in the solution should be understood.
- Understanding that acidic solution is dependent on the concentration of H^+ ions in relation to other ions in the solution is needed. An increase of ions (H^+ or OH^-) when an acid or a base are respectively dissolved in it will determine the solutions' acidity or basicity. A solution with an H^+ ion concentration higher than OH^- ion concentration would then be deemed acidic and a solution with OH^- ions higher than H^+ would be basic. If the concentration of the two ions is stoichiometrically equivalent, the solution would be deemed neutral.
- The symbolic representation of an aqueous solution should be understood. The dissociation of water, where water at equilibrium is represented by

$K_w = [H^+] \times [OH^-]$ (equilibrium constant) = 10^{14} and $[H^+] = [OH^-]$: $H_2O \rightleftharpoons OH^-$ (aq) + H^+ (aq).

- It should be understood that any change in any of the components of the equilibrium will affect other components in one way or the other (Le Chatelier's principle).

In the formation of concept clusters such as this one (Exhibit 4.1), the purpose was to establish the knowledge of students about the concept. What could not be established directly, though, was the form or relations in which the knowledge was held. However, this could be established through the interpretation of the responses to related responses within and/or across clusters.

(ii) Student's understanding and use of concepts and the researcher's explanation and interpretations

The three types of knowledge (declarative, procedural and conditional) were analysed in the three ways proposed earlier by Reif (1985) to specify concepts unambiguously.

- Specification of a concept

Specification of a concept is a demonstration of an individual's declarative knowledge. This knowledge was mostly demonstrated by responses to the first research sub-question.

Research sub-question 1: What is students' understanding of selected chemistry concepts and processes before engaging in a first-year practical work activity?

The individual responses (as they appear in Exhibit 4.1) are assumed to demonstrate the student's representation of his or her knowledge of the concepts in question. In other words, the answers to the questions in the cluster are a direct declaration of facts, meanings and principles, as the student understands them. For example, in case **A** an acidic solution (Q.4.1.2) is "a solution that has a high concentration of H^+ ions". This response is not viable, but it is what the student understands an acidic solution to mean. The view here is that this is the understanding the student would use when asked to apply her knowledge of an aqueous acidic solution at that particular time. This response was a direct translation from the definition of an Arrhenius acid in Q.4.1.1. The student's response illustrates declarative knowledge.

- Instantiation

The responses in Exhibit 4.1 are used to demonstrate student's (in case **A**) understanding of concepts. These responses are used in this analysis as a referent of how the student used her understanding and/or meaning of an aqueous acidic solution (Q.4.1.2). This section of the analysis focused on the student's instantiation. This knowledge is demonstrated when an individual constructs understanding and/or meaning of a concept. The analysis of instantiation was a response to the second research sub-question:

Research sub-question 2: How do students use their prior knowledge of selected chemistry concepts and processes to construct understanding and generate meaning during learning?

The information that the researcher could infer from student **A**'s knowledge base (Exhibit 4.1) is that it lacked the necessary knowledge elements to enable instantiation. Most of the knowledge was either non-existent or incomplete. To successfully construct understanding one needs information with sufficient and necessary elements of that knowledge. In this cluster of responses, the student only succeeded in demonstrating declarative knowledge; and in some instances this knowledge was incomplete (Q.4.1.2). Complete declarative knowledge is important in knowledge construction – in order to describe an aqueous acidic solution the student first had to establish relations between or among related concepts. The student attempted this when responding to Q.4.1.2. The student attempted to relate the response to the response in Q.4.1.1 where "increase" was associated with "high" (see illustration 4.1 below).

Illustration 4.1

Differentiate between an Arrhenius and a Boasted-Lowry acid.

S: Arrhenius' acids ***increase*** *the concentration of* H^+ *ions* when dissolved in *water* while Bronsted-Lowry's acids are proton donors.

You are told that an aqueous solution is acidic. What does this mean?

S: It means the solution has a ***high*** *concentration of* H^+ *ions.*

However, it was not possible because the student opted to use her declarative knowledge of an Arrhenius acid without first restructuring it to make sense of the requirements of the question. The other contributing factor to this inability was the incompleteness (in Q.4.1.2) of the student's relevant prior knowledge.

The student could not demonstrate an understanding of the relationship of the H^+ ions and OH^- ions in the solution. The absence or unavailability of this understanding may have contributed to her inability to explain her reasons for her responses in Q.4.1.3 and Q.4.1.4. According to Gunstone and White (1992), one must have some information about the concept in memory to understand it, because a valid measure of understanding involves eliciting the "full set of elements the person has in memory about it" (p. 6). In the case of this study, the full sets of elements are elements found in the specification knowledge. Barsalou (1993) describes these elements as feature lists that must be complete and well organised to help provide a satisfactory account of conceptual content.

On the basis of the information the student provided, and the inferred information (Exhibit 4.1) it could be concluded that the student possessed elements of information relevant to constructing meaning of the concept of interest. But they were not necessarily a full set of elements to construct meaning. According to Smith (1991), understanding occurs when two criteria, "connectedness" and "usefulness in social context", are satisfied. In the case of this student, only one criterion, namely connectedness, was satisfied (in terms of her responses to Q.4.1.1 and Q.4.1.2) within this cluster of responses. The student appropriately represented the idea of an "increase in H^+ ions" from Arrhenius' definition of an acid with a "high concentration of H^+

ions" in an acidic solution. But, based on the interpretation of Q.4.1.1 and Q.4.2.2 it can be concluded that, in terms of her prior knowledge, she had insufficient and isolated bits of prior knowledge about acids, and it was limited to operational definitions. The student's information was incomplete and poorly structured, and she was unable to construct meaning of an aqueous acidic solution.

The structure or organisations of information and the second criterion, "usefulness in social context", are somehow related: to be able to use information or knowledge it must be well structured or well organised. Prawat (1989) defines the ability to use knowledge relevantly as "transfer". Transfer would therefore be possible if the information an individual possesses is well structured or well organised. In the case of this student, transfer failed because of a lack of well-organised structure in her knowledge base.

- Error prevention

It is possible to prevent errors if a student can apply his/her "conditional knowledge", or if the student demonstrates a high level of reflective awareness. Conditional knowledge, according to Dochy and Alexander (1995), is "knowing when and where" to do or act in a situation (i.e. when and where a particular action should be taken). According to Prawat (1989), being able to apply this knowledge is dependent on two interrelated factors, namely the ability to "organise" and the "reflective awareness" of the individual.

When responding to the two questions (Q.4.1.1 and Q.4.1.2), the student apparently had relevant information in her knowledge base that could be used to construct a viable response to what an aqueous acidic solution meant. The information was relevant because the student could define an acid in both the Arrhenius and the Bronsted-Lowry theories. What was however not apparent, was how this knowledge was represented, especially in terms of the triangular nature of matter, i.e. at macro, micro (particulate) and symbolic levels. The conclusion that could be made from the responses is that the student could not use her understanding or the information implied in Q.4.1.3 (of the existence of H^+ and OH^- ions in an aqueous solution). This knowledge was inferred in her response to Q.4.1.3. The student lacked reflective awareness in her responses. Therefore, the student had reached a stage of "access failure" (Prawat, 1989). She could not respond with viable answers. The student could not use her reflective awareness to reorganise the knowledge that she had in her knowledge base or which was implied in the question (Q.4.1.3) to respond correctly or prevent an error in describing an aqueous acidic solution.

(iii) Synthesis

The aim of the study was to understand the quality of prior knowledge students possessed and its effect on the learning of certain concepts in chemistry and the construction of understanding and generation of meaning of those concepts. It is apparent that the quality of this student's prior knowledge affected her ability to respond viably to questions posed. What is also significant about this student's prior knowledge is that it was more declarative than procedural or conditional. The student's instantiation and error prevention were limited with regards to responding to questions. The student's prior knowledge at the time the empirical study was conducted is aptly summarised by Bransford, Sherwood, Vye, and Rieser, (1986) when they say:

> … the fact that people have acquired knowledge that is relevant to a particular situation provides no guarantee that *access* will occur (p.1080).

The reason why there was access failure on the part of this student needs to be further explained. Access failure for this student could be attributed mainly to the student's *mental models* of the nature of matter in chemistry. Had the student accurately represented (through mental models) the three levels at which matter existed, the recognition of the existence of all the ions and molecules (including H^+ and OH^- from H_2O) would have been reflected on and their concentrations considered in responding to the question on what an aqueous acidic solution meant. Access depends on organisation, and *good organisation*, according to Polya (1973), is more important than the extent of one's knowledge. Good organisation is made possible by the correct and accurate construction of mental models.

The following example serves to demonstrate that the student's knowledge was not well organised: The student used the Arrhenius definition to indicate that acidity is associated with the concentration of H^+ ions, but failed to do the same for linking OH^- and H^+ to an aqueous solution that was apparent in her understanding (Q.4.1.3 and Q.4.1.4). When an acid dissociates in water it releases and increases H^+ ions, but this does not necessarily make them higher than other ions (e.g. OH^-) in the aqueous solution. The contribution or effect of the OH^- ions in this solution was disregarded; hence the word "high" was used instead of "higher". In describing acidity, the student assumed (inference) the H^+ ions to be the only ions in the solution.

In conclusion, the student could not satisfy the criteria of usefulness – it could not function to describe an aqueous acidic solution. Both the student's procedural and conditional knowledge had limitations or were absent. Both the instantiation and error correction or prevention aspects (of the specification knowledge) were not satisfied.

Exhibit 4.2

Presented data

Questions, student's responses and data sources

Q.4.2.1: Why is ethanoic acid considered a weak acid? (O&I)

S: It is a weak acid … CH_3COOH is not ionised completely because there are still H^+ ions within the CH_3COO^-.

Q.4.2.2: What is the difference between a strong and a weak acid? (O&I)

S: Acid that dissociates or ionises completely is an aqueous solution.

Q.4.2.3: Differentiate between an Arrhenius and a Bronsted-Lowry acid. (PKST: Q.6)

S: Arrhenius' acids *increase the concentration of H^+ ions* when dissolved in *water* while Bronsted-Lowry's acids are proton donors.

(i) Description of specification knowledge (memorandum)

The concept of focus of this cluster was "acid strength". An understanding of the concept of acid strength by the student with specific reference to a weak or strong acid was sought in this category. There are three possible concepts of acids and bases the student could have used to respond to the questions on acid strength: the "Arrhenius concept", the "Bronsted-Lowry concept" or the "Lewis concept". As indicated earlier, the extent of understanding depends on the quality of the individual's prior knowledge. Therefore, the knowledge to describe a concept is specified to assess prior knowledge *fairly* and *unambiguously*. In the case of this study, the quality of knowledge was determined by specifying the knowledge the students should have demonstrated in order to be considered to possess adequate knowledge in describing a concept. With regard to describing acid strength in this cluster, the requirements included demonstrating the following:

- That the Arrhenius concept is based on the fact that acid-base reactions involve transfer of H^+ ions from one substance to another and is restricted to aqueous solutions.
- That the Bronsted-Lowry concept emphasises proton transfer but, unlike the Arrhenius concept, is not restricted to aqueous solutions.
- That the Lewis concept is based on the fact that a pair of electrons is transferred from one molecule to another. (An acid is an electron pair acceptor and a base is an electron pair donor.)
- That the use of the Arrhenius and the Bronsted-Lowry concepts will distinguish between a weak and a strong acid.
- That strong acids or bases are electrolytes that completely ionise in a solution, while weak acids or bases are electrolytes that partly ionise in solution (Brown *et al*., 2003).
- That a substance is completely ionised when all its *constituent ions* are dissociated in the solution and none of its original molecules remain un-dissociated. For example, hydrochloric acid (HCl) is a strong acid or strong electrolyte and dissociates into H^+ ions and Cl^- ions. Acetic acid (CH_3COOH), on the other hand, is a weak acid or weak electrolyte that partially dissociates into its constituent ions (CH_3COO^- and H^+).
- That partial dissociation occurs when only a fraction of original molecules dissociate into ions, and relative strengths of acids and bases are therefore determined by the extent to which they dissociate in a solution.
- That strong acids completely transfer their protons to water, leaving no un-dissociated molecules in the solution, while strong acids are more reactive than weak acids when the reactivity depends only on the

concentration of the H^+ (aq) ions (Brown *et. al*., 2003). For example, hydrofluoric acid (HF) is a weak acid but it is very reactive and vigorously attacks many substances including glass. This reactivity is due to the combined action of H^+ (aq) and F^- (aq).

(ii) The student's understanding and use of concepts and the researcher's explanation and interpretations

Responses to the questions in this concept cluster (Exhibit 4.2) aimed to elicit the student's understanding and use or construction of the concept of acid strength. The objective was to understand how the elements of the student's knowledge base on the topic of acids and bases were integrated to construct understanding or generate meaning during learning and /or in responding to questions.

- Specification of a concept

Specification of a concept had to be illustrated with responses to the first research sub-question. In this concept cluster, case **A** appears to have understood what a weak acid was (Q.4.2.1). In her response she indicated a weak acid to be a substance that is not completely ionised. This is a viable response. But did the student understand what complete ionisation meant? For this student, complete ionisation meant the complete decomposition of a molecule of acid or ionisation of all H atoms into H^+ ions from the molecule. This inference is supported by her response: "… there are still H^+ ions in the CH_3COO^-". The important question in this analysis (in terms of the quality of the responses) was whether the student would be able to instantiate this understanding or knowledge.

- Instantiation

Instantiation, like specification of a concept, demonstrates one's conceptual knowledge. In Q.4.2.2 it was expected that the student would apply her understanding of a weak acid to differentiate it from a strong acid. Since it is apparent that the student only stated what a weak acid is without understanding what it meant, it would have been difficult for her to apply this knowledge. What the student did instead was to define a strong acid. The student could not indicate the difference between a weak acid and a strong acid. In her response (Q.4.2.1) to whether ethanoic acid (CH_3COOH) was a weak acid or not, her response (in terms of declarative knowledge) was viable, because according to the Arrhenius concept of acids and bases weak acids ionise partly in an aqueous solution. However, based on the reason the student gave of what partial ionisation meant it is apparent that the student did not understand the term "ionisation".

If she understood the term ionisation, there is a high probability that she could have been able to establish the difference between a weak and strong acid in terms of Arrhenius's definition of acids. Understanding of the term "ionisation" played an important role in the construction of meaning of the concept of *acid strength*. This student had a misconception about the term ionisation. Instead, its understanding was derived from the student's prior understanding (Q.4.2.3) of an acid according to the Arrhenius concept of acids and bases. This understanding led the student to have a fixation on the H^+ ion whenever an explanation of acid strength was sought. The term "ionisation" was used to refer to the release of H^+ ions, irrespective of where the H^+ was located in the molecule (see Q.4.2.1).

The student's focus was on the H^+ as the only *active* ion in the solution. The CH_3COO^- was not considered as another ion making up the CH_3COOH molecule. Therefore, it can be concluded that the response was mainly influenced by the student's understanding of an acid as a substance which, when dissolved in an aqueous solution, *increases or releases the* H^+ ions (Exhibit 4.1). The answer was constructed from this understanding. In terms of the effect of prior knowledge, this can be attributed to restructuring. The student had relevant prior knowledge, but the information as it was conceived or stored was not organised so it could be restructured to enable viable construction of required response. In this cluster, information was not well organised to construct understanding or generate meaning of weak or strong acids. Information or prior knowledge in the form in which it was stored was therefore not *accessible*, since the student could not reflect on terms such as ionisation and decomposition when referring to the formation of ions (and not the formation of constituent atoms of the CH_3COOH molecule).

- Error prevention

The student's quality of knowledge in Q.4.2.1 and Q.4.2.2 was such that it would not be useful for reflection. The student did not understand what ionisation meant. Her understanding, as far as could be determined, was that it involves the "removal" of H^+ ions from a molecule. Even if the student was able to use this knowledge appropriately, it would not have helped (because of her understanding of what ionization meant in this case). It is apparent that the student's understanding of complete ionisation had *an inhibiting effect* on her ability to use knowledge appropriately. The fact that the student interpreted "complete ionisation" as meaning decomposition of the CH_3COOH molecule to release all H^+ ions indicates a lack of appropriate knowledge to reflect on the matter. In Q.4.2.2, the student did not complete the answer. Instead of differentiating between a weak and a strong acid, the student elected to define a strong acid. These responses suggest that the student could also not reflect on the difference in the absence of correct and well-organised, complete knowledge. Hence the student's reflective awareness was inhibited by *unavailable* knowledge. Failure to prevent errors is an indication of lack of or limited conditional knowledge. That is, *when and where* to use knowledge.

(ii) Synthesis

The student's response to Q.4.2.1 could be explained by looking at two aspects that affect one's knowledge and its usage: It could be attributed to the student's prior knowledge and the nature of the subject matter. As far as the prior knowledge is concerned, it could be concluded that the student's prior knowledge was incomplete (in which case it would have been difficult to organise it and make sense of). The prior knowledge was incomplete in that the focus of describing a weak acid was based on the H^+ ions at the expense of the whole CH_3COOH molecule its constituent ions and the composition of an aqueous solution. The diminished understanding of the term "ionisation" affected, to a large extent, viability of the student's knowledge to construct understanding and generate meaning of both weak and strong acids.

The student's understanding of the nature of the subject matter, on the other hand, lacked imagery in terms of the triangular representation of matter (macro, micro and symbolic levels). This suggests that there was a *gap* between the student's mental model and conceptual model (see Figure 2) in terms of how a weak and/or strong acid dissociated in an aqueous solution. It could therefore be concluded that the student lacked the ability to *restructure her prior knowledge* to construct new knowledge of acid strength. Without complete and correct knowledge, new knowledge or well-organised knowledge construction becomes difficult (if not impossible).

Exhibit 4.3

Presented data

Questions, student's responses and data sources

Q.4.3.1: Presume that you are titrating a weak acid (e.g. CH_3COOH) and a strong base (e.g. NaOH). What would the expression "equivalence point" mean in this process? (PKST: Q.12)

S: The amount of titrant is chemically equal to the amount of analyte.

Q.4.3.2: Why is there a *temporary* colour change in a solution whenever the NaOH solution drops in the centre of the solution during titration (analyte)?

(O&I)

S: Because it has *reached* the equivalence point.

Q.4.3.4: What is meant by equivalence point? (O&I)

S: Amount of **vinegar** is equivalent to **NaOH** in the solution.

Q.4.3.5: What is meant by endpoint? (O&I)

S: When we observe colour change.

Q.4.3.6: What is the purpose of an indicator in a titration? (O&I)

S: To find the colour change and *observe* the pH of the solution.

Snippets from the practical work report (PWR).

Method

- Pipette 10 ml of vinegar solution into a 100 ml volumetric flask.
- Add deionised water to the graduation mark.
- Pipette 25 ml of vinegar solution into a conical flask.
- Titrate the NaOH solution into the conical flask until (the) colour changes.

Observation

At the beginning of the titration, there is a colour change at the centre of the conical flask.

As the process continues, the colour turned dark pink (endpoint). The colour change is due the indicator added …

Calculated percentage: 461% (estimated %: 4 to 6%).

Conclusion

% content of ethanoic acid in vinegar solution is very high.

(i) Description of specific knowledge (memorandum)

The focus in this cluster was on two important and related concepts in the titration processes. Students often confuse the use of the concepts "equivalence point" and "endpoint" in titration processes. Titrations are processes used by chemists and students to determine the concentration of a particular solute in a solution. Titration involves combining a sample of the solution with a reagent of known concentration (standard solution). During the titration process, increments of a standard solution are added to the sample being analysed ("analyte") until the reaction is stoichiometrically complete. The reaction is stoichiometrically complete when the analyte and the titrant are equivalent. This is the point when the exact stoichiometric amount of titrant has been added. This point is termed the "equivalence point" of the titration. The "endpoint", on the other hand, (Petrucci, Harwood & Herring, 2002) is "the point in a titration at which the indicator changes color" (p.726).

The indicator in acid-base titrations is a substance whose colour changes according to the pH of the solution to which it is added (Petrucci, *et al*., 2002).

In this category it was expected that students would demonstrate their understanding and knowledge of what each of the concepts meant, where each of them occurred, and how each could be identified during the titration process. The chemical processes or reactions leading to colour change also needed explaining. It was also expected that students demonstrate their understanding of the difference between equivalence point and endpoint, and show when an endpoint and equivalence point respectively were reached during titrations.

(ii) The student's understanding and use of concepts: Analysis and explanation

The aim in this cluster was to understand how the student understood and used the concepts "equivalence point" and "endpoint". Students usually confuse the meaning of these two concepts. In analysing their understanding, the focus was on the perceived 'confusion' commonly found in the use of the concepts. The analysis in this cluster (like in the previous one) entailed the three aspects of specification knowledge used by Reif (1985) when analysing a concept.

- Specification of a concept

In the case of this student, one cannot regard the responses to represent an unambiguous scientific knowledge (Exhibit 4.3). That is, they could not lead to a clearly interpretable scientific knowledge. For example, in responding to Q.4.3.1, the student described equivalence point as the point at which reacting species (titrant and analyte) are "chemically equal". In this response (Q.4.3.1) the student only demonstrated *familiarity* with what equivalence point meant (in terms of the process where reacting species combine). The word "equal" is scientifically misleading in the case of chemical reactions. Instead, the student should have used "equivalence" to demonstrate that reactions take place in different ratio relationships. This response indicates a recollection of previous experience with the term "stoichiometric equivalence". The response indicates the student's declarative knowledge of equivalence point. (The equivalence point is the point at which reacting species are combined in equal molar amounts based on the reactants relationship according to a balanced equation.). The student managed to specify equivalence point, even if the specification was not completely without ambiguity. The question that arises then is: Can incomplete knowledge be applied?

- Instantiation

According to Dochy, knowledge *availability,* which is affected or affects accessibility (see Figure 8) is the ability to utilise resources. Availability and accessibility are functions of organisation and awareness (Dochy, 1992). For knowledge to be applied successfully it has to be complete and well organised. Organised knowledge is when key concepts and procedures are connected to provide the glue that holds the cognitive structure together (Dochy, 1992). The response in Q.4.3.2 suggests that the student's prior knowledge of equivalence point (Exhibit 4.3) did not provide a "glue to hold the cognitive structure together" – the form in which this student's knowledge was organised did not make her aware of what the *temporary* colour change indicated in terms of the meaning of equivalence point (or endpoint for that matter). In her practical work report (Exhibit 4.3), the student indicated her observation of this colour change and the fact that it was not the endpoint. The response clearly indicates that this knowledge was not *complete, available and/or accessible*; therefore the response could not have been viable. Inaccessible knowledge illustrates *poorly organised* knowledge. The organisation of knowledge in this instance was such that it could not be activated to be immediately usable to construct a viable response.

In Q.4.3.2 the term "temporary" was supposed to have *hinted* to the student that the titration was still in progress. It is apparent from her response (Q.4.3.2) that the student did not consider the *meaning* of the term "temporary" in the process of titration. The equivalence point could not have been reached while the colour kept reverting to the original colour during titration. The student did not, in this case, demonstrate connectedness. The student did not appropriately represent the idea of "temporary change" or connect it with her understanding of equivalence point. Therefore, it can be inferred that the student regarded *equivalence point and endpoint* to mean the same thing, and are both indicated by a colour change (considering the responses in Q.4.3.4 and Q.4.3.5). However, it should be noted that equivalence point is *effectively* the endpoint (as it is the point at which the amounts of reacting species are stoichiometrically equal). But the endpoint is not necessarily the equivalence point. Endpoint (colour change) is an indication of the fact that the equivalence point has been exceeded.

- Error prevention

As indicated earlier (Prawat, 1989), accessibility depends on one's "organisation" and "reflective awareness". In the case of this student, reflective awareness was lacking. For example, the student failed to recognise the importance of the term "temporary" in Q.4.3.2 to guide her responses. In responding to questions involving colour change, the student did not reflect on the nature of the subject matter she was dealing with. Colour change involves a chemical reaction. A symbolic representation at micro level (through her mental model) of a reaction of an indicator in different media would have facilitated a better response. The indicator exhibits different colours in different media:

$$\mathbf{HIn\ (aq) + H_2O\ (l) \rightleftharpoons H_3O^+\ (aq) + In^-\ (aq)}$$

Colour A **Colour B**

Phenolphthalein
(Colourless) **(Pink)** **pH 8, 00 - 10, 00**

In the case of this particular practical activity, (where a base reacts with an acid) phenolphthalein was the indicator. In an acid medium, phenolphthalein is colourless and in a basic medium phenolphthalein turns pink. In her responses, the student viewed colour change only at the macro level. That is, physical change of colour (see the response to Q.4.3.1; vinegar and not CH_3COOH is reacting with NaOH). This representation illustrates the influence of incompleteness in one's prior knowledge. The student's prior knowledge did not enhance understanding or relational use of knowledge in this practical work activity.

The student did not consider or reflect on all the steps she had undertaken in her calculation to reach her final answer. The student did realise that her answer was far too high, but could not remedy the situation. The student was unable to retrace her steps in the method to determine what could have been the source of the "high percentage content" in her calculations. This inability to reflect on her prior knowledge indicates a lack of reflective awareness in her manipulations during practical work. For example, the dilution factor of the original solution of vinegar was not considered in her calculations. The density of the vinegar solution was not used anywhere in her calculations. The student's knowledge was not well organised. She could not construct understanding from the information at her disposal.

(iii) Synthesis

The student's responses (on equivalence point, endpoint and colour change of the indicator) could be explained in terms of the effects of prior knowledge and the nature of subject matter. Some responses could be attributed to the effect of prior knowledge (Q.4.3.1 to Q.4.3.6). The prior knowledge was *unavailable, inaccessible and not well structured*. The fact that the student managed to explain what an equivalence point was (Q.4.3.1) and the purpose of an indicator (Q.4.3.6) did not mean she could use this knowledge appropriately. This is so because the knowledge was not accessible. It was not accessible because it was not well organised. If it was well organised, it may have been possible for the student to restructure it to construct new understanding or meaning. The level of the subject matter at which the student understood reactions affected the student's understanding of the chemical process involved. In this case, the student did not view the reaction at micro level (see Figure 4); for example, she used the term "vinegar" instead of "acetic acid" (CH_3COOH) reacting with NaOH.

Exhibit 4.4

Presented data

Questions, student's responses and data sources

Q.4.4.1: Differentiate between a *dilute* solution of a *weak* acid and a *concentrated* solution of a weak acid. Illustrate your answer with a relevant example. *(*PKST: Q.5)

S: Dilute weak acid does not produce gaseous gas while concentrated acid produces substances. $H_2CO_3 \rightarrow CO_2^- + H^+$

$H_2CO_3 \rightarrow H_2O^+ + HCO_3^-$

Q.4.4.2: What is the difference between a strong and a weak acid? (O&I)

S: Acid that dissociates or ionises completely in an aqueous solution.

Q.4.4.3: Why is ethanoic acid considered a weak acid? (O&I)

S: It is a weak acid … CH_3COOH is not ionised completely because there are still H^+ ions within the CH_3COO^-.

Q.4.4.4: Calculate the molarity of HCl with a density of 1,057 g/ml and purity of 12% by mass. (PKST: Q16)

S: D = m/v; 1,057 = (12/100)/v

v = 0,12351

c = m/mv

= 0, 03 mol/dm^3

Q.4.4.5: Illustrate how 500 ml of a 6 M solution of NaOH is diluted by a factor of *25.* (PKST: Q.20)

S: 6 x 500/25

Q.4.4.6. What do you understand by the term "concentration"? (O&I)

S: Concentration is the ratio of moles per volume (n/v).

Q.4.4.7: What do you mean by the term "dilute"? (O&I)

S: To reduce the concentration of vinegar.

Q.4.4.8: What is the concentration of ethanoic acid in vinegar after dilution? Is it high or low? (O&I)

S: It is not yet known.

Q.4.4.9: What happens if it adds the volume? (O&I)

S: It reduces the concentration.

(i) Description of specification knowledge (memorandum)

In performing practical work, students are expected to demonstrate their skills in carrying out their work. Skills are the part of the knowledge system that includes declarative, procedural and conditional knowledge. There are decisions to be taken in terms of which step to follow and how to respond in a situation where the process is not yielding results as expected. Students are therefore expected to integrate their knowledge to successfully complete their practical work tasks. The questions in this section are based on practical work activities. Some of the questions may not make sense in the absence of a context. However, the context will be explained in the interpretation of the students' responses to these questions.

The concept of interest in this category was "concentration". Concentration refers to the number of moles (n) of an acid per volume (v) measured in dm^3 or cm^3 of a given quantity of solvent. Solutions with different concentrations are referred to as either dilute or concentrated in relation to each other. For example, a dilute solution of a weak acid refers to the relatively small number of moles (n) of acid per relatively large volume (v) of solvent; whereas a concentrated solution refers to a relatively larger number of moles per relatively smaller volume of solvent, e.g. 0, 01 M ethanoic acid is dilute, as compared to a 0, 1 M solution of ethanoic acid. Concentration of a solution can be expressed in a variety of ways, for example as moles per litre of solution (molarity), moles per kilogram of solution (molality), percentage concentration (m/m per cent; m/v per cent; v/v per cent), parts per million (ppm) or mg per litre. In this activity, concentration was expressed in moles per litre and percentage mass per mass. Students were expected to demonstrate their ability to manipulate figures of masses and volumes through dilutions to determine the concentrations of solutions.

In addition, this section looked at the concept of concentration with specific focus on the relationship between a dilute and a concentrated solution. The student was expected to relate the two terms (dilute and concentrated) through the manipulation of the relationship between concentration (c), number of moles (n) and volume (v). It was therefore required that the student demonstrates declarative, procedural and conditional knowledge (since the manipulation of a relationship between factors or concepts requires that one is conversant with what they are, what they mean and when and where they are applicable). The terms "dilute solution" and "concentrated solution" are related to concentration by the equation:

$$C = n/v \qquad (1)$$

where C = concentration, n = number of moles of solute in the solution, and v = volume of the solution. They are related to dilute and concentrated solutions in the sense that a dilute solution refers to a solution with a relatively small number of moles (n) dissolved in a relatively large volume (v) of solvent, and a concentrated solution is a solution in which a relatively larger number of moles (n) is dissolved in a relatively small volume (v) of solvent. These relationships can be demonstrated mathematically as follows:

$$C = n/v \text{ where } C = 1/v \text{ and } C \propto n \qquad (2)$$

Questions in this category were aimed at probing the student's understanding of terms associated with concentration and strength in solution chemistry. Generally, students confuse "dilute" for "weak" and "concentrated" for "strong". This results in students being unable to apply the concepts with understanding in practice (for example, in calculations or during practical work activities).

(ii) The student's understanding and use of concepts: Analysis and explanation

Concepts for analysis in this cluster (in terms of concept specification, instantiation and error prevention) were a "dilute solution of an acid", "weak acid" and a "concentrated solution".

- Specification of a concept

The student's response (Q.4.4.1) reaffirmed the ‘confusion’ students demonstrate when dealing with the terms "dilute" and "weak" with regard to acids and bases. In this response, the student misconstrued a weak acid with a dilute solution of a weak acid. A "dilute solution of a weak acid" is described (by the student) in terms of the dissociation of an acid when describing a weak or a strong acid. The understanding of the two reactions, which are not necessarily a correct representation of the reaction, confirms the misconception. A weak acid or a strong acid behaviour/definition can be demonstrated symbolically with an equation that illustrates that they ionise completely or partially. A dilute and/or concentrated solution can be explained by expressing their concentrations in moles/dm^3 or any other expression of concentration and comparing them (e.g. 0, 02 M and 0, 05 M CH_3COOH represent a dilute and concentrated solutions respectively).

The student's representation of a dilute and/or concentrated acid had no relation to the solution concentration or number of moles in a given volume of solution. The two terms (dilute and concentrated) were not at all described in the relationship c = n/v or the number of moles per given volume of a solution. When asked to define "concentration" (Q.4.4.6), the student responded with a correct answer (c = n/v). This was followed with a correct response in Q.4.4.7 when asked to explain what the term "dilute" meant, although the student had a language deficiency in responding to the question. It was apparent that the student had knowledge of facts (declarative knowledge) about the terms.

- Instantiation

All meaning, according to Pines (1985), is relational and elucidation of meaning is possible through the analysis of relations. The student's responses in the case of this cluster did not generate meaning as her knowledge was not well organised for building relations. The student's knowledge was made up of isolated concepts, which made it difficult for applicable knowledge construction. As indicated earlier, the student had declarative knowledge that she could not access for procedural purposes. As isolated facts, her knowledge could not readily be used, since it was not structured in a comprehensible way that could be easily activated to make sense of the incoming information. Therefore it can be concluded that the student's knowledge was of a poor quality. It was not available and could not be accessed owing to a lack of quality structure. For example, the responses to

Q.4.4.4 and Q.4.4.5 required the restructuring of declarative knowledge of density (d = m/v) and that of concentration (c = n/v) for procedural purposes. The student was expected to restructure her declarative knowledge into procedural knowledge to respond to both these questions. In Q.4.4.4, the student demonstrated that parts of her knowledge were correct (e.g. d = m/v). But her prior knowledge was incomplete. Incomplete knowledge in this case inhibited the ability to arrive at a correct answer. The responses to Q.4.4.6, Q.4.4.7 and Q.4.4.8 confirm the conclusion that this researcher made earlier about the poor organisation of the student's knowledge. If dilution means reduction of concentration (Q.4.4.5) and if volume increases (Q.4.4.7) reduces concentration, then the concentration in Q.4.4.8 should have been low.

- Error prevention

The student's responses indicate a lack of reflection during learning and using her responses in other questions to prevent or correct mistakes committed. According to Prawat (1989), knowledge that lacks organisation tends to affect the individual's reflective awareness. In the case of this student, the lack of reflective awareness was evident in most of the related questions (Q.4.4.5 to Q.4.4.9).

(iii) Synthesis

Although it was not directly discussed, one of the factors that contributed to this student's inability to respond viably to many questions in this cluster was the nature of the subject matter. The subject here is chemistry. The student could not respond viably as she could not construct mental models because her imagery of matter was not well represented. For example, the student could not differentiate between "dilute" and "weak" because she represented concentration in terms of the strength of an acid. Instead of using moles and volume, the student used symbolic representation of a dissociating acid. This indicates confusion in the student's organisation of knowledge in her knowledge base. Poorly organised knowledge cannot be used successfully to construct understanding or generate meaning, as it is difficult to access such knowledge.

4.3.2 Analysis: Case B (Exhibits 4.5 to 4.8)

Exhibit 4.5

Presented data

Questions, student's responses and data sources

Q.4.5.1: Differentiate between an Arrhenius and a Bronsted-Lowry acid. (PKST: Q.6)
S: Arrhenius: Acid when react liberate/release hydrogen ion H^{+}.
Bronsted-Lowry acid: Acid is a proton donor/it donates protons.
Q.4.5.2: As the hydrogen ion concentration of an aqueous solution increases, the hydroxide ion concentration of this solution will – (1) increase; (2) decrease; or (3) remain the same? (PKST: Q.3)
S: Hydroxide ion (OH^{-}) will also increase because if you increase the concentration of acid in chemical reaction you also increase the concentration of base.
Q.4.5.3: You are told that an aqueous solution is acidic. What does this mean? (PKST: Q.1)
S: It means that every acid is in the form of water molecules.
Q.4.5.4: In terms of the Bronsted-Lowry definition of acids and bases, what is a strong acid and a weak acid? (PKST: Q.8)
S: Strong acid is acid that ionises completely in water.
Weak acid is acid that ionises partly in water.

(i) Description of specification knowledge (memorandum)

For a description of specification knowledge (memorandum), refer to exhibit 4.1 above.

(ii) The student's understanding and use of concepts: Analysis and explanation

Analysis in this cluster of questions and responses focused on the concept "acidity". This concept, like any other concept, is a product of construction of other concepts or terms. The four questions were clustered together to elicit information from the student's knowledge base that, on the basis of the described specification knowledge, is considered relevant and sufficient to construct the meaning of an aqueous acidic solution. The cluster was constructed such that it could enable inferences from the student's knowledge base to demonstrate the student's understanding of the three ways concepts can be understood when described (namely specification of concepts, instantiation and error prevention).

- Specification of a concept

As concepts are built from other concepts or terms, three of the four questions in this cluster (Q.4.5.1, Q.4.5.2 and Q.4.5.4) were posed to determine the student's basic understanding of the concepts and/or terms with the potential to describe an "aqueous acidic" solution (Q.4.5.3). In his response to these questions, the student demonstrated his declarative knowledge of the concepts. This does not necessarily mean the responses were all viable, but they indicate how the student 'understood' the concepts. It is apparent from the student's responses that he was able to state or define most terms or principles with information that could be used to construct understanding of an *acidic aqueous solution*. The question here is whether the student was able to use this knowledge to construct meaning of an acidic solution?

- Instantiation

Instantiation, as indicated earlier, has to do with one's ability to apply knowledge. Asking the definition of an aqueous acidic solution was aimed at allowing the student to construct the meaning of an aqueous acidic solution. The ability to describe an aqueous acidic solution also depended on the student's understanding of what an aqueous solution is. The student's response to Q.4.5.2, although incorrect, is an indication that the student understood that ions are formed when water dissociated. It was also apparent that the student interpreted an increase in hydrogen ion to come from the dissociation of the solvent rather than the introduction of the ion in the aqueous solution itself. In other words, the student described the *dissociation of the water molecule* ($H_2O \rightleftharpoons H^+$ (aq) + OH^-(aq)) instead of the introduction of an H^+ ion. This understanding resulted in the construction of the response as indicated below:

As the *hydrogen ion* concentration of an aqueous solution increases, *the hydroxide-ion* concentration of this solution will – (1) increase; (2) decrease; or (3) remain the same?

Response: Hydroxide ion (OH^-) will also *increase* because if you increase the concentration of acid in chemical reaction you also increase the concentration of base.

The emphasis of the student's responses on the aqueous solution is also apparent from his answer to Q.4.5.3. The *aqueous acidic solution* the student refers to here is the form in which the water exists rather than the excess H^+ ions (from the dissociating acid) in water solvent. The impression created from these responses is that the student's mental models were inaccurate in terms of the equilibrium of the aqueous solution. That is, they could not enhance his ability to construct a viable response of what an aqueous acidic solution was.

The student's inability to construct a viable meaning of an aqueous acidic solution suggests the form or structure of his knowledge was not organised in a way in which accurate mental models could be constructed. In addition the type of responses given could be the student's imagery of the nature of the subject matter. In this case, the student's view of matter is more at the macro level than at the two other levels of matter (micro and symbolic levels). The student managed to associate "aqueous" with water, but could not represent it at the appropriate symbolic level where ions (H^+ and OH^-), and not the water molecule, are active in the determination of an aqueous solution. The symbolic representation would have enhanced a valid response to Q.4.5.2 and to describe an acidic solution in Q.4.5.3 (as an excess of H^+ ions in the solution).

- Error prevention

In the interpretation of concepts (Reif, 1985), students need adequate knowledge to prevent errors and to correct them appropriately when they have been committed. It is apparent from this student's responses (knowledge base) that his ability to prevent errors was inadequate. For example, his response to Q.4.5.2 indicates his incorrect mental model of the chemical reaction involved in this particular reaction. An aqueous solution is the dissociation of a water molecule as a reaction: ($H_2O \rightleftharpoons H^+$ (aq) + OH^-(aq)). Introducing extra H^+ (aq) ions would *upset* the equilibrium when the extra H^+ ions react with OH^- ions (Le Chatelier's principle). The student's response indicates his failure to reconstruct his current knowledge to construct meaning based on the chemical reaction involved. According to Prawat (1989), knowledge that lacks organisation tends to affect the individual's reflective awareness.

(iii) Synthesis

In this cluster, the student demonstrated his declarative knowledge of the concepts or terms that could be used to describe or construct meaning of an *aqueous acidic* solution. But his poor organisation or structure of that knowledge is apparent. The student could not reorganise his knowledge to construct meaning with the information at his disposal. The information, as indicated earlier, was more declarative. In addition, the student had difficulty with the nature of matter. In most of the responses, the student's view of matter was mostly at a macro level. The nature of the subject matter inhibited the student’s ability to give valid responses to a large extent. The inappropriate use of the nature of the subject matter resulted in the student failing to recognise mistakes and correct them appropriately when the need to do so arose.

Exhibit 4.6

Presented data

Questions, student's responses and data sources

Q.4.6.1: In terms of the Bronsted-Lowry definition of acids and bases, what is a strong acid and a weak acid? (PKST: Q.8)

S: A strong acid is acid that ionises completely in water. Weak acid is acid that ionises partly in water.

Q.4.6.2: Is acetic acid a weak acid or a strong acid? (O&I)

S: Acetic acid is a weak acid because it ionises incompletely in water.

Q.4.6.3: What does it mean to ionise incompletely? (O&I)

S: The participant cannot explain what it means to "incomplete ionise".

Q.4.6.4: Demonstrate how a weak acid ionises "incompletely". (O&I)

S: … Not all H^+ ions have ionised … there are still three H^+ ions in the CH_3COO^- ion.

(i) Description of specification knowledge (memorandum)

For a description of specifications knowledge (memorandum), refer to Exhibit 4.2 above.

(ii) The student's understanding and use of concepts: Analysis and explanation

In this cluster, just like in the clusters analysed earlier, the objective was to understand how students use their previously acquired knowledge of concepts in chemistry and ways of thinking to generate meaning of related concepts. The aim of this study was to understand this meaning generation within the realm of three types of knowledge, namely declarative knowledge, procedural knowledge and conditional knowledge. The concept to be analysed in this cluster was "acid strength".

- Specification of a concept

According to Phye (1997), specification of a concept demonstrates one's declarative knowledge. The student's responses in exhibit 4.6 give an indication of his knowledge of the concepts relevant (according to the specification knowledge) to the construction of the concept "acid strength". However, the responses do not suggest that the student responded (Exhibit 4.6) viably, but the responses are an indication of the student's understanding of such concepts or terms. What is important is the student's understanding and use in a practical situation.

- Instantiation

In responding to Q.4.6.1 it is apparent in the researcher's view that the student was familiar with the terms "strong acid" and "weak acid" (according to the Bronsted-Lowry concept of acids and bases). The term "familiarity" was advisedly used here to avoid committing oneself to terms such as "knowledge". Knowing has a variety of meanings depending on one's view of what learning and/or knowledge is. For example, Schwartz and Reisberg (1991) refer to knowing as implying that one has experienced something or thought about it before and remembering the experience. As the purpose of this study was to establish if students understood certain concepts and their use, it would have been inappropriate to use the term "knowledge" before it was established.

In terms of declarative knowledge, the student's knowledge of the weak and strong acids was viable (Q.4.6.1). All the terms ("ionise", "complete" and "aqueous solution") were appropriately used according to the requirements of the specification knowledge. However, in his attempt to describe why acetic acid was a weak acid the student used the term "incompletely" to construct the meaning of a weak acid, instead of "partly". It is apparent in the context of the question and the student's response that the term was used as an opposite of the term "completely" (as it is associated with the term "weak", which is the opposite of "strong"). Generally, the student managed to demonstrate his declarative knowledge of strong and weak acids. The only limitation in his response was his limited vocabulary – in his use of the term "incompletely".

In Q.4.6.4, the context of the statement "ionise incompletely" is apparent. That is, the ionisation referred to here is not the formation of ions in an aqueous solution of CH_3COOH, represented by the dissociation of acetic acid in water;

$$\mathbf{CH_3COOH \rightleftharpoons CH_3COO^-_{(aq)} + H^+_{(aq)}}.$$

It is a total disintegration or decomposition of the acetic acid molecule (CH_3COOH) into its constituent atoms. The influence of this conception could be traced back to the term "complete", and the student should have used his understanding of what an acid is according to the Arrhenius concept (i.e. the formation of H^+ ions in aqueous solution). In this case, the student expected all H atoms to be ionised to H^+ ions.

The student's understanding of ionisation demonstrated in Q.4.6.4 was influenced by the term "complete" in the definition of a strong acid:

Demonstrate how a weak acid ionises "incompletely".
Response: … *Not all H^+* ions have ionised … there *are still three H^+ ions in the CH_3COO^- ion.*

On the strength of this understanding the student developed a mental model of the decomposition of the acid to form H^+ ions from all the hydrogen atoms found in the acetic acid molecule. The fact that the student just associated *strong* with *weak* and *complete* with *incomplete* is apparent in his response to Q.4.6.3. The student could not explain what it meant in the context it was used.

- Error prevention

The successful performance of any task is, according to Reif (1985), facilitated by one's awareness of likely errors and pitfalls. In a learning situation, teachers warn their students of mistakes commonly made when responding to questions. In responding to questions, students should also reflect on their responses to make sure that they make scientific sense. This reflection is only possible if the student has relevant and ‘correct’ knowledge. In other words, this knowledge must be available and/or accessible to the student. It is apparent that most of this student's knowledge was declarative.

His inability to use knowledge to reflect on his current knowledge is referred to as the problem of "inert knowledge" (Phye, 1997; Prawat, 1989). Students thus have relevant knowledge (in whatever form) but cannot recall or use it. This student's declarative knowledge could not be reconstructed to make sense of what a weak acid was compared to a strong acid or vice versa.

(iii) Synthesis

As indicated earlier, the purpose of this analysis was to elicit understanding of student's declarative, procedural and conditional knowledge. It can be concluded that the student's knowledge was affected in diverse ways. The assumption is that the outcomes of learning depend on the quality of the characteristics of prior knowledge (Dochy, 1992). These characteristics intervene in the learning process or its outcomes and causing interference in learning. With this student there was some interference as a result of these qualities. In response to Q.4.6.1, the student demonstrated his declarative knowledge of a strong and weak acid despite the fact that he used inappropriate terms. The student's declarative knowledge can be described as reasonable, complete and correct. The responses to Q.4.6.2 to Q.4.6.4 indicate that declarative knowledge does not necessarily translate into procedural and/or conditional knowledge. In other words, knowledge was available but could not be used to respond to other situations.

In his response to Q.4.6.4, "complete ionisation" was misconstrued with disintegration. That is, the knowledge of strong and weak acids was not accessible because it was not well structured. It was not in a form that could be used to represent correct information about what ionisation means in describing a weak and a strong acid. In conclusion, procedural and conditional knowledge were not such that they could be applied and/or reflect on.

Exhibit 4.7

Presented data

Questions, student's responses and data sources

Q.4.7.1: What is meant by equivalence point? (Q&I)

S: When the amount of reagent is equivalent to the amount of the analyte.

Q.4.7.2: How does equivalence point differ from endpoint? (Q&I)

S: Endpoint is when the reaction is judged to be complete.

Q.4.7.3: When do you judge the reaction to be complete? (Q&I)

S: When the colour changes.

Q.4.7.4: When does the colour change? (Q&I)

S: At (the) endpoint standard amount is higher than analyte.

Q.4.7.5: Presume that you are titrating a weak acid (e.g. CH_3COOH) and a strong base (e.g. NaOH). What would the expression "equivalence point" mean in this process? (PKST: Q.12)

S: Equivalence point means that the amount of weak acid (CH_3COOH) is equal to the amount of strong base (NaOH).

Snippets from the practical work report (PWR)

Method/procedure

) The solution of vinegar (10, 00 cm^3) was *added to a pipette* and the solution was transferred to a volumetric flask and diluted to the mark with distilled water.

i) And *25 cm^3 pipette of vinegar* solution was transferred to two conical flasks.

Calculations

A: D = m/v

m = d x v

= 1,045g/cm^3 x 15, 00 = 15,675 g % 15,675/21, 3 cm^3 x 100 = 73, 6%

Observation

The solution of vinegar changes from light colour to pink.

The pink colour shows that there is a solution of ethanoic acid.

Conclusions

This shows *that vinegar* is a strong acid when reacting with sodium hydroxide and it liberates water and ethanoic acid.

(i) Description of specification knowledge (memorandum)

For a description of specification knowledge (memorandum), refer to Exhibit 4.3 above.

(i) The student's understanding and use of concepts: Analysis and explanation

This cluster of questions and responses was compiled to indicate how the student would specify or understand and apply the concepts in a practical situation. This clustering was based on Pines' (1985) assertion that the meaning individuals attach to a word and their conceptual framework make them knowledgeable in a particular area depending on the relations they form. The cluster was aimed at demonstrating the relations used by the student to construct meaning from his responses. From these relations conclusions could be made to understand how the student understood and used a specific concept. In the case of this cluster, the concepts of interest were "equivalence point" and "endpoint".

- Specification of a concept

In his response to what "equivalence point" meant (Q.4.7.1), it is apparent that *equivalence* for this student meant *equal*. Equivalence can only mean *equal* in a 1:1 ratio reaction. If the student was aware of the differences and similarities between equivalence and equal, the point of the reaction ratio could have been indicated. The failure or inability to indicate this shows his incomplete understanding of the concept. In responding to Q.4.7.2 the student did not differentiate between the two concepts, but elected to explain what endpoint is. But from his response to Q.4.7.4 and Q.4.7.5 it appears that the student could differentiate between the two concepts. The conclusion is that the student demonstrated his declarative knowledge of the two concepts. But would it be possible for him to use this understanding in practice?

- Instantiation

Many students (Reif, 1985) are unable to apply concepts in particular situations, even if they have managed to define them. In the case of this student, the description of “equivalence point” made it difficult to apply it to all practical situations. Describing it as "equal" could only be applied if the reactants were reacting in a 1:1 ratio (such as in the case of the reaction between acetic acid (CH_3COOH) and sodium hydroxide (NaOH)). This description of equivalence in reactions with different reaction ratios would not be applicable. It is evident from his responses that the student regarded equivalence as equal – regardless of the ratio in which the reactants reacted. This response indicates the level at which the student constructed his mental models as far as the nature and reaction of matter was concerned. The student viewed the reaction at a macro level of matter. The student's description of *endpoint* seems to be the same as that of the *equivalence* point. The explanation of endpoint is superficial (in the sense that it is viewed only as colour change and not as a different type of reaction between different chemical species). The student also did not view the reaction as ethanoic acid (CH_3COOH) reacting with sodium hydroxide (NaOH), but a reaction of *vinegar* – there was no reaction equation in all his calculations in the practical work report.

The superficial nature of the student's response is confirmed in Q.4.7.4, where the amount of reactants rather than the reaction taking place is preferred to explain the colour changes. The colour change is "seen" in terms of the amounts of reacting species. This response reinforces the idea that the student's mental models were constructed at a macro level. The important chemical reaction between the indicator and the two different media (acid and base) were not part of the student's constructed mental model:

$HIn\ (aq) + H_2O\ (l) \rightleftharpoons H_3O^+\ (aq) + In^-\ (aq)$

Colour A **Colour B**

Phenolphthalein
(Colourless) **(Pink)** **pH 8, 00–10, 00**

The quality of the student's responses to this cluster of concepts could have been affected significantly by the three prior knowledge factors (namely incompleteness, organisation and structure). For example, in describing equivalence point it is apparent the student's understanding was limited. Equivalence was synonymously described as equal without specifying the reaction ratio. This description would have a negative effect on its use in cases where the reaction was not 1:1. The student's inability to recognise the limitation of his description of equivalence indicates that his knowledge was incomplete and poorly organised.

Finally, what is significant about the student's understanding of the two concepts in relation to each other and their use is the use of "amount of reactants" instead of the reaction behind the changes (e.g. colour change). This shows that the student constructed his mental models of what transpired at the macro level. The question is whether the student was in any position to reflect on the viability of his responses to the questions (Exhibit 4.7)?

- Error prevention

One is able to prevent an error or correct it if you have relevant prior knowledge to do so. In other words, an error can be prevented if the individual has available or accessible information or knowledge that can help him or her reflect on the errors committed. This student's knowledge was in such a form that it could not be accessed. It is apparent that the student had declarative knowledge that was memorised. In this form, knowledge is difficult to restructure as it was conceived without understanding. Therefore, the student could not use this knowledge in a practical situation when it was demanded of him (Exhibit 4.7). For example, in Q.4.7.5 equivalence point is not necessarily a point when the amount (depending on what amount means) of weak acid is equal (equal needs explanation) to the amount of strong base. The term "equal" can only be used provided the reaction is a 1:1 reaction (in molar terms). The student did not reflect on the stoichiometric relationship. Error prevention is about decision-making. Decision-making requires the application of knowledge. Without information to construct such knowledge, errors cannot be prevented or corrected.

(ii) Synthesis

Generally, the student demonstrated incomplete knowledge of what the terms "equivalence point" and "endpoint" meant. Most of his understanding was superficial. It was superficial in the sense that the understanding was not based on the reactions that took place in a solution. The explanations were based on the *amount* of solution and the changing of physical appearances rather than on the chemical reactions behind the changes. This could be a demonstration of the level at which the student was taught about the subject matter. That is, the student may not have been aware of any other level at which matter could be described. It could also be that the levels were not explained to him during teaching to enable him to construct mental models on the basis of the different levels at which matter exists. Without relevant mental models it becomes difficult, or even impossible, to construct viable knowledge or understanding. It is also difficult or impossible to reflect without relevant mental models.

Exhibit 4.8

Presented data

Questions, student's responses and data sources

Q.4.8.1: Differentiate between a *dilute* solution of a weak acid and a *concentrated* solution of a weak acid. (PKST: Q.5)

S: Dilute solution of a weak acid is an acid, which has *lots of water* in the solution whereas concentrated solution of a weak acid is an acid which have (a) *small amount of water* in the solution.

Q.4.8.2: What do you mean by *concentration*? (O&I)

S: Number of *moles* per given *volume.*

Q.4.8.3: Why do you dry glassware before using it? (Student dries conical flask before adding sample) (O&I)

S: We need the amount of vinegar only … not of vinegar and deionised water.

Q.4.8.4:.Why do you need the amount of vinegar only? (O&I)

S: It is a method … I do not know, Sir.

Q. 4.8.5: Why did you not dry the volumetric flask in which a sample was diluted? (The student did not dry the volumetric flask in which a dilute solution was prepared as was the case with other apparatus) (O&I)

S: Because we use deionised water to *dilute* the vinegar sample.

(The student becomes suspicious and retorts: This action will change the concentration of the solution, Sir.)

Q.4.8.6: How will it change the concentration of the solution? (O&I)

S: I do not know, but it will change the concentration of the solution … more deionised water will be added.

Q.4.8.7: Will it change the number of moles of acid to be titrated? (O&I)

S: The size of the container determines the concentration.

Q.4.8.8: What do you mean by concentration? (O&I)

S: Number of moles per given volume.

Snippets from the practical work report

Method/procedure

(ii) The solution of vinegar (10, 00 cm^3) was *added to a pipette* and the solution was transferred to a volumetric flask and diluted to the mark with distilled water.

(iii) And *25 cm^3 pipette of vinegar solution* was transferred to two conical flasks.

Calculations

A: d = m/v

m = d x v

= 1,045g/cm^3 x 15, 00 = 15,675 g % 15,675/21, 3 cm^3 x 100 = 73, 6%.

(i) Description of specification knowledge (memorandum)

For a description of specification knowledge (memorandum), refer to Exhibit 4.4 above.

(ii) The student's understanding and use of concepts: Analysis and explanation

The concepts of "dilution" and "concentration" are concepts many students find difficult to use in practice, especially during calculations. It becomes even more difficult if students are confronted with the new learning environment of practical work. Most students entering higher education in South Africa come from a background where resources for science learning were limited (in some instances non-existent). It is not surprising to find students in a first-year chemistry class failing to use concepts such as dilution or concentration in practical work situations. This failure is prevalent when students have to do calculations where dilution factors have to be taken into consideration. In this cluster, the understanding of concentration and dilution (specification of a concept, its instantiation and error prevention) was probed.

- Specification of a concept

Exhibit 4.8 above contains the questions and responses from the student that in the view of the researcher could assist in highlighting the student's understanding of “concentration” and “dilution”. To understand a concept, one must first be able to specify it. In his response to the first question (Q.4.8.1), the student established important relationships in terms of what dilute and concentrated solutions were. In describing a dilute and concentrated solution, it appears that the student was familiar with the relationship (in amount) between the solvent (water) and the solute (acid). The solvent was viewed as being more in amount in a dilute solution as compared to the solute. In a concentrated solution, the solvent (water) is less than the solute (acid). The student's response indicates an understanding of dilute and concentrated solutions. Could this understanding, in the form it was specified, be applied in practice?

- Instantiation

In his response to what concentration means (Q.4.8.2), the student managed to indicate concentration as a function of moles and volume; but he could not do the same in Q.4.8.1. In his response to Q.4.8.1, "dilute" and "concentrated" were described in terms of the solvent (water). The student viewed the solute as a constant. From this response it is clear that the description of concentration was algorithmic. The student could not use this knowledge to develop a mental model of a relationship (c = n/v). It can be concluded therefore that the understanding of solvent and acid were at a macro level, since they were not considered in relation to c = n/v. If this had been the case, the student would have used this relationship to differentiate between a dilute and concentrated solution of acetic acid (as described in the specification knowledge above). It can be concluded that the structure of the student's knowledge resulted in relevant knowledge being unavailable and therefore not being accessible.

In Q.4.8.3 the student's knowledge of the relationship c = n/v was probed. The researcher’s aim was to test what dilution factor the solvent introduced in the solution of a particular concentration. In responding to this question, the student was supposed to have used his understanding or develop a mental model around the c = n/v relationship. On further questioning (Q.4.8.6), the student recalled that the addition of the solvent would change the concentration, but could not indicate how the concentration would change (whether it would decrease or increase). This shows that the student's knowledge was isolated and not accessible. Knowledge in this form cannot be restructured to construct new understanding or meaning. Inability to reconstruct knowledge is also evident in the student's failure to refer/consider the dilution of the original sample after 10 cm^3 of the solution was transferred into the volumetric flask during the practical work task. Nowhere in the calculation was the acid content considered (Exhibit 4.8).

- Error prevention

The ability to interpret information or a concept depends on one's relevant and adequate prior knowledge. This student only demonstrated declarative knowledge. With this limited knowledge, the reflective awareness to prevent errors (by application of conditional knowledge) appeared impossible. Conditional knowledge was lacking because the student could not make connections (connectedness) between components (c = n/v) of his declarative knowledge. This resulted in a failure to decide what the effect of adding a solvent would be on the concentration. The student was also unable to realise that any addition of the solvent to the sample affected the relationship between all terms in c = n/v. This reflection was missing in the students' manipulation of apparatus and the sample during the experimental work.

(iii) Synthesis

In this cluster of questions and responses, the student had to demonstrate declarative knowledge of the concepts "dilute" and "concentration". However, the student could not successfully use this knowledge in a practical situation. This became evident when the student was asked to explain his actions during practical work. In the case of this student, it can be attributed to *incompleteness* of knowledge (when parts of prior knowledge are correct but incomplete). The ‘correct’ parts of this student's responses were his reference to dilution and concentration in terms of the amount of the solvent and the amount of the solute (only referred to as acid) and the description of concentration in terms of moles per given volume. The incomplete part was his inability to use the description of concentration to differentiate a dilute acid from a concentrated acid through the manipulation of the relationship c = n/v. This is understandable because the student (in defining a dilute/concentrated solution) only managed to use the amount of solvent (H_2O) without using the number of moles of the solute.

Another factor that inhibited learning in this case was the factor of *availability* of knowledge. From the student's response to Q.4.8.2 it is clear that he had the knowledge but could not use it when it was required. This can be attributed to a failure to make *connections* between available knowledge (c = n/v with dilute and concentration) and its "usefulness". The knowledge of c = n/v was not activated. A third factor inhibiting this student's learning was the factor of *accessibility*. Prior knowledge was not immediately available, as it was not organised in the correct structure for use. Available knowledge is easily activated when it is accessible. Prior knowledge is more accessible if it is well organised. As far as this student is concerned, his knowledge was not well organised, since it could not be accessed when required.

In conclusion, this student's responses revealed the availability of knowledge as declarative knowledge, but limited only to knowledge specification. The student was unable to apply his knowledge and prevent errors in the responses given. The student's three types of knowledge (declarative, procedural and conditional) were not sufficiently integrated to help in responding appropriately to questions.

4.3.3 Analysis: Case C (Exhibits 4.9 to 4.12)

Exhibit 4.9

Presented data

Questions, student's responses and data source

Q.4.9.1: Differentiate between an Arrhenius and a Bronsted-Lowry acid. (PKST: Q.6)

S: Arrhenius acid is a substance that increases H^+ ions in aqueous solution whereas with Bronsted-Lowry acid it is a proton donor.

Q.4.9.2: You are told that an aqueous solution is acidic. What does this mean? (PKST: Q.1)

S: It means that it contains hydrogen ions.

Q.4.9.3: Was the solution in the conical flask before titration acidic or basic? (O&I)

S: Acidic because the pH was less than seven.

Q.4.9.4: What was the pH after the colour change? (O&I).

S: Neutral.

Q .4.9.5: In which solution is the phenolphthalein pink? (O&I).

S: It is pink in a base.

Q.4.9.6: If it is pink in a base, what would its pH be after endpoint? (O&I).

S: More than seven … it is neutral?

Q.4.9.7: When is a solution neutral? (O&I).

S: When its pH is equal to seven.

Q.4.9.8: When pH = 7, what is the concentration of OH^- in relation to the concentration of H^+ ions? (O&I).

S: $[OH^-] = [H^+]$

(i) Specification knowledge

For a description of specification knowledge (memorandum), refer to Exhibit 4.1 above.

(ii) The student's understanding and use of concepts: Analysis and explanation

The responses to the eight questions in this cluster were chunked together to reflect on the student's domain-specific prior knowledge (declarative, procedural and conditional knowledge) of the concept "acidity". The eight questions were aimed to draw as much of the student's knowledge as possible and her ability to use it in constructing understanding of an "aqueous acidic" solution. In the formation of concept clusters such as this one, the purpose is to establish the relevant knowledge the student has about or related to the concept. It could not be established initially in which form this knowledge was held. But eventually it could be established by interpreting the responses to different related questions using Reif's (1985) three ways of describing a concept.

- Specification of a concept

In her response to Q.4.9.2, the student described the meaning of an aqueous acidic solution as a substance containing hydrogen ions. This description was apparently derived from an interpretation of the Arrhenius and Bronsted-Lowry concepts of acids and bases. The acidity of the solution was described in terms of the pH of the solution. This shows that the student made a connection between acidity and pH. This relationship was further confirmed by the student's response to Q.4.9.7 and Q.4.9.8. In Q.4.9.8, the student showed her understanding of the dependence of acidity on the concentration of H^+ ions in the solution. The question however, is whether this understanding could be applied appropriately in practice?

- Instantiation

In her response to Q.4.9.1, the student described an acid according to both the Arrhenius and Bronsted-Lowry concepts. As the question was not restrictive in how to differentiate, any differentiation that met the minimum requirements of the specification knowledge was acceptable. This student showed the difference between one acid dissolved in water increasing H^+ ions in solution (Arrhenius) while the other (Bronsted-Lowry) donates a proton.

This response was viable at a declarative level. In responding to Q.4.9.2, the student made a connection between the H^+ ions and acidity. However, this was not adequate to construct meaning of an "aqueous acidic" solution. The student could not access relevant information or knowledge enabling her to construct meaning of an aqueous acidic solution. The question one can ask is whether the student had this information or knowledge. The responses to Q.4.9.8 and Q.4.9.3 show that the student 'understood' the meaning of the relationship between H^+ and OH^- ions (in terms of what an acidic, a basic and a neutral solution are):

Was the solution in the conical flask before titration *acidic or basic?*
Response: Acidic because the *pH was less than seven*.
When pH = 7, what is the concentration of OH^- in relation to the concentration of H^+ ions?
Response: $[OH^-] = [H^+]$

The connection made by the student between related information and the information at her disposal did however not translate into usefulness in the social context (Glynn & Smith, 1991). The solution containing hydrogen ions did not necessarily make it acidic. An aqueous acidic solution contains both hydrogen and hydroxide ions, but with more hydrogen ions than hydroxide ions. In describing an acidic solution, it could be concluded that the student had adequate and relevant knowledge, but it was *inaccessible* because it was not *well structured*. The student's knowledge could thus not be used to construct a viable meaning of what an aqueous acidic solution was. Was the student aware of the information she had?

- Error prevention

In Q.4.9.3 to Q.4.9.8, the student's understanding was further probed to establish her reflection of the relation between acidity and pH (OH^- and H^+). In her response to whether the vinegar solution in the conical flask was acidic or basic, the student responded by using the pH scale. Her response that the pH was less than seven was *correct*; but (in this practical work) there was no way of determining this except by way of the student's previously learned declarative knowledge about the pH scale and acidity (i.e. that the pH of an acid is below seven and that of a base is above seven and the colour of the phenolphthalein in the solution is colourless in an acid and pink in a base).

The response to Q.4.9.4 illustrates that the student did not follow the reaction process in terms of the reacting species (OH^- and H^+ ions). That is the acid and base reaction that took place. The student did not engage with the reaction at the appropriate level, for example, at the molecular and symbolic levels. Her response to Q.4.9.4 was focused on the outcome of a reaction between equal amounts of an acid and a base where the resulting solution became neutral. The fact that the student responded that the *pH was neutral* instead of giving a value of the pH indicated the student's selective attention approach in her response. The answer of "neutral" was based on the acid-base reaction (the reaction of an acid and a base resulting in a neutral solution provided the amounts at the end of the reaction are equivalent). This also indicates that the student's knowledge was *incomplete* since not every acid-base reaction results in a neutral solution; this only happens when the number of moles of the reacting species is stoichiometrically equivalent.

(iii) Synthesis

The questions in this cluster were aimed at establishing the student's knowledge (declarative, procedural and conditional) and her ability to integrate this knowledge and use it appropriately in practical situations. Questions 4.9.5 to 4.9.8 were aimed at helping the student reconstruct the information she had about acid-base titration with phenolphthalein as an indicator. From the responses given it is clear that the student had relevant prior knowledge, although it was more pronounced as declarative knowledge. What was "missing" though was the ability to reorganise this information or knowledge to make connections and eventually make it useful in practical situations.

In responding to these questions, the student had sufficient knowledge available to construct viable responses to the questions. Dochy (1992) believes that individuals with a great deal of prior knowledge process new information by means of a different cognitive structure than those with little domain-specific prior knowledge. Individuals with more prior knowledge have alternative routes with which they can process and elaborate on information. In responding to Q.4.9.5 to Q.4.9.8 the student demonstrated that she had relevant prior knowledge. However, this knowledge appears to have been poorly organised for successful constructing understanding or generating meaning of an aqueous acidic solution.

Exhibit 4.10

Presented data

Questions, participant's responses and data source

Q.4.10.1: Differentiate between an Arrhenius and a Bronsted-Lowry acid. (PKST: Q.6)

S: Arrhenius acid is a substance that increases H^+ ions in aqueous solution whereas with Bronsted-Lowry acid is a proton donor.

Q.4.10.2: In terms of the Bronsted-Lowry definition of acids and bases, what is a strong and a weak acid? (PKST: Q.8)

S: A strong acid is an acid that ionises completely in aqueous solution; weak acid is a weak electrolyte that exists mostly as molecules in aqueous solution.

Q.4.10.3: As the hydrogen ion concentration of an aqueous solution increases, the hydroxide ion concentration of this solution will – (1) increase; (2) decrease; or (3) remain the same? (PKST: Q.3)

S: Decrease because if the acid is strong then the base is weak.

(i) Description of specification knowledge (memorandum)

For a description of specification knowledge (memorandum), refer to Exhibit 4.2 above.

(ii) The student's understanding and use of concepts: Analysis and explanation

The aim with this concept cluster was to demonstrate the student's understanding of "acid strength", and the application of the principle of acid strength. As there are three ways in which acids and bases can be described at this level of learning (first-year university chemistry), the focus in this cluster was on the Arrhenius and Bronsted-Lowry concepts. The student's understanding was probed using Reif's (1985) three-step approach of describing a concept.

- Specification of a concept

In her response to Q.4.10.1, the student demonstrated her ability to define or explain (declarative knowledge) the two concepts (Arrhenius and Bronsted-Lowry). In addition (Q.4.10.2), the student managed to describe what a "weak" and a "strong" acid were. Possession of declarative knowledge was earlier described as no guarantee for translating it into usable knowledge. In fact, Reif (1985) believes that the mere definition of concepts or statements of principle are insufficient building blocks in enabling one to perform complex intellectual tasks.

- Instantiation

This student's response to Q.4.10.3 confirms the notion that the mere definition or description of a concept is not sufficient for one to perform a complex intellectual task. In her response to Q.4.10.3 the student could not explain why there should be a decrease in OH^- ion concentration when the H^+ ion concentration is increased. This illustrates the student's misconception of what is meant by a "strong" or "weak" acid. The view in this study is that the student misconstrued concentration with acid strength. The student's response (that the increase in H^+ ions decreases the OH^- ion) was viable. The response to any question is a product of one's mental model. It is apparent from the student's responses that they were based on her understanding of what an acid was according to the Arrhenius and Bronsted-Lowry concepts. It is also apparent that the student had an understanding of what a strong and weak acid were based on the two concepts (Arrhenius and Bronsted-Lowry).

The student used her understanding of a strong and a weak acid (Q.4.10.2) to explain her choice of the term "decrease" in her response to Q.4.10.3. Her reasoning was due to her understanding of a strong acid in terms of the Arrhenius concept. The base or hydroxide ions in this case were interpreted as a "weak acid" that partly ionises in an aqueous solution with a low number of ions; hence the response: "decrease". The response appears not to have been derived from the reaction of the hydrogen ions and hydroxide ions where the concentration of the hydroxide is reduced or decreased because of the reaction with the hydrogen ions to form the water molecule in the reaction: $H^+(aq) + OH^-(aq) \rightleftharpoons H_2O$).

- Error prevention

Viability of responses in any learning situation depends on the quality of one's prior knowledge. Knowledge that is complete and correct helps reflective awareness. Without reflective awareness errors in one's knowledge (responses) become difficult to detect and correct. This student's prior knowledge was inadequate to construct mental models for differentiating between a weak and strong acid and the concentration of H^+ and OH^- ions in the solution.

(iii) Synthesis

What can the student's responses be attributed to? It is apparent that the student could construct a viable response based on the knowledge demonstrated. However, there was a problem with how the information or knowledge was conceived and stored in her long-term memory. Most of this student's knowledge was declarative and could have been conceived through memorisation. For example, the student misconstrued acid strength with concentration because she indicated that a strong acid decreased the weak base (in her response to Q.4.10.3). With regard to the quality of her prior knowledge, the response and the reason for the response could be attributed to the form in which her knowledge was structured at the time of responding to the question (Q.4.10.3). The structure and organisation of knowledge affected the construction of viable knowledge. The knowledge was inaccessible. It was poorly structured or organised and could not be used viably in practical situations. This student's knowledge was correct (declarative knowledge), but could not be applied as procedural and/or conditional knowledge to build any relational meanings.

Exhibit 4.11

Presented data

Questions, student's responses and data source

Q.4.11.1: Presume that you are titrating a weak acid (e.g. CH_3COOH) and a strong base (e.g. NaOH). What would the expression "equivalence point" mean in this process? (PKST: Q.12)
S: It will mean that the amount of added strong acid is equivalent to the base.
Q.4.11.2: What do you understand by the term endpoint in a titration process?
(O&I)
S: It indicates physical change.
Q.4.11.3: Differentiate between equivalence point and endpoint? (O&I)
S: Equivalence point indicates that amount of added standard reagent is equal to analyte.
Q.4.11.4: Which one between equivalence point and endpoint occurs first in a titration? (O&I)
S: Endpoint.
Q.4.11.5: Why do you think endpoint comes before equivalence point? (O&I)
S: Endpoint means after everything has happened ... No, Sir … this one is confusing. I am sticking to my first answer. Maybe I understand the meaning … I do not know what happens. (After a while): I think it is equivalence point … before we see any changes (in colour).

Snippets from the practical work report

Method

- 10 cm^3 of vinegar was transferred into a 100 cm^3 volumetric flask with a pipette with distilled water up to the mark.
- 25 cm^3 of vinegar was transferred into 2 conical flasks using a pipette.
- Three drops of phenolphthalein were added …
- NaOH was then titrated … until the endpoint was reached.

Calculations

See Exhibit 4.12

Observation

The colour of the vinegar changed from colourless to pink after titration with NaOH.

(i) Description of specific knowledge (memorandum)

For a description of specification knowledge (memorandum), refer to Exhibit 4.3 above.

(ii) The student's understanding and use of concepts: Analysis and explanation

Titration processes play an important role in the teaching of chemistry at first-year level. On this basis, if a good foundation of chemistry is to be built students should as part of learning chemistry, understand titrations and the chemical processes involved. In this cluster of questions and responses, two related and often confused concepts were the focus. These two concepts are "endpoint" and "equivalence point". The understanding of these concepts is generally superficial, with little emphasis on the reaction behind it. In this analysis, just like in previous analyses so far, the understanding of how students understand the two concepts was confined to specification of a concept, its instantiation and error prevention in the use of concepts.

- Specification of a concept

Specification of a concept (Reif, 1985) indicates the meaning of the concept according to specified rules that ensure that the concept is unambiguously identified and is understood as clearly interpretable scientific knowledge. In the case of this analysis it meant ensuring the accurate interpretation of what the student understood the concept to mean and its use in practical situations. Students were subjected to a prior knowledge state test, where they were required to elaborate on their responses so that the researcher could establish the extent of their understanding of the concepts. Some of the responses were drawn from the interview with the researcher (Exhibit 4.11).

- Instantiation

In her responses to questions Q.4.11.1 and Q.4.11.2, the student's understanding of "equivalence point" and "endpoint" respectively was probed. Her response to Q.4.11.1 shows uncertainty as to the meaning of equivalence point. However, it was clarified by the response to Q.4.11.3. In her response to what "equivalence" means, the student equated it to "equal". Endpoint, on the other hand (Q.4.11.2), was viewed as describing only a physical change of the solution (i.e. colour change).

"Equal" in stoichiometric terms needs further explanation, as it does not necessarily indicate equivalence. Equivalence point takes into consideration the fact that a balanced chemical reaction needs to be considered if a decision on *equality* of reactants is to be pronounced. The student's knowledge in her use of the term “equal” was indicative of incomplete knowledge. Equal (in terms of the reacting species) does not necessarily make them equivalent unless what is being measured and the units used are specified. A balanced equation determines whether equal can describe equivalent. In a 1:1 ratio reaction, "equal" means "equivalent". In the context of the practical work activity for this task, the student's response was viable since the reaction was a 1:1 ratio between acetic acid (CH_3COOH) and sodium hydroxide ($NaOH$).

Her response to Q.4.11.2 reflects her view of the reaction in the titration mixture. The student's developed mental model of what takes place in the reaction vessel did not indicate knowledge of the micro or symbolic levels of the changing of matter in the reaction. To describe endpoint simply as a physical change (colour change) gives no indication that the student viewed the change as a chemical reaction of the indicator or the type of medium (basic or acidic). This inference is confirmed by the student's "incorrect" response to Q.4.11.4. On further probing, the student changed her mind (Q.4.11.5).

This illustrates the process of reorganising prior knowledge in the student's response to the question:

> Why do you think endpoint comes before equivalence point?
> Response: Endpoint means after everything has happened...
> No, Sir … this one is confusing.
> I am sticking to my first answer.
> Maybe I understand the meaning …
> I do not know what happens …
> (After a while): I think it is equivalence point …
> before we see any changes (in colour).

It can be concluded that the student had knowledge about equivalence point and endpoint, but it was not immediately available, as it was not well structured to immediately meet the requirements of the incoming information. Regarding the change of colour of the indicator, it is apparent that the student had no prior knowledge of how (chemical reactions) and when the colour of the indicator changes. In conclusion, the student's knowledge of equivalence point, endpoint and indicator reaction was incomplete.

- Error prevention

The extent to which a person understands his or her domain's knowledge determines the extent to which he or she can use this knowledge to reflect, detect and correct errors. Initially, the student made errors regarding the terms used. For example, she used the term equal synonymously with equivalent, indicating that she did not have adequate knowledge to develop a mental model of what each of these terms meant in practice. However, in her processing of the difference between “endpoint” and “equivalence” point the student managed to use her understanding of what physical change meant to arrive at a viable response of which one of the two terms came first in a titration process.

Another example of failure to reflect on one's prior knowledge is the inability to use information relevantly. In her calculations, the student used the formula d = m/v and the volume from the titration to determine the mass of the acetic acid in the vinegar solution, instead of the volume of the sample. This resulted in the percentage content calculated at 94, 88%. This result should have prompted the student to reconsider her calculations (since it was far higher than the estimated 4% to 6% indicated in the method).

In conclusion, the student generally did not reflect on the knowledge she possessed or constructed during learning.

(iii) Synthesis

The student managed to describe the two concepts without necessarily understanding what they meant in practical terms. The student was able to indicate what they signified without being able to demonstrate with relevant chemical reactions what the significance of, for example, equivalence meant when an acid or base reacted with an indicator. The conclusion one can make from this is that the student's knowledge was incomplete and therefore difficult to instantiate in a practical situation. In addition, the effect of the student's view of the nature of matter contributed to her inability to understand and apply this knowledge in practice. The student did not use all the information at her disposal or constructed during the practical work activities. The dilution of the solution, for example, was not considered in her calculations. No reaction equation was used for a molar relationship between reacting species.

Exhibit 4.12

Presented data

Questions, participant's responses and data source

Q.4.12.1: Is it possible to weigh vinegar in solution form? (O&I)

S: Yes … but you must have a solid.

Q.4.12.2: How would you determine the mass of vinegar? (O&I)

S: By using the density.

Q. 4.12.3: Show the calculations to determine the % content of CH_3COOH. (PWR)

S: D = m/v

Mass = 1,045 g/cm^3 x 22, 7 = 23, 72

% CH_3COOH = 23, 72/25 x 100 = 94, 88%

Q.4.12.4: Calculate the molarity of HCl with a density of 1,057 g/cm^3 and purity 12% by mass. (PKST: Q.16)

S: C = n/v

= 1,057/10^3) x 1 mol HCl/36, 45 g

= 28, 99 mol x 12 g

= 3, 479 mol/l

Q.4.12.5: Differentiate between a *dilute* solution of a *weak* acid and a *concentrated* solution of a weak acid. Illustrate your answer with a relevant example. (PKST: Q.5)

S: Dilute solution of a weak acid: A solution which dissolve(s) completely is a weak acid: $CH_3COOH \rightleftharpoons CH_3COO^- + H^+$. Concentrated = that ionised partly: $NH_4 \rightarrow NH_3^+ + H_3O^+$.

Q.4.12.6: What would have been the effect if a 5-molar solution of NaOH was used in the place of a 0, 1-molar solution in this titration? (O&I)

S: Using a high concentration solution will increase the % of ethanoic acid in the vinegar solution. If you use 5 M NaOH endpoint is quickly reached.

Q. 4.12.7: What makes endpoint to be reached quickly? (O&I)

The student cannot account for this phenomenon.

Q.4.12.8: As the hydrogen ion concentration of an *aqueous solution* increases, the hydroxide ion concentration of this solution will – (1) increase; (2) decrease; or (3) remain the same? (PKST: Q.3)

S: Decrease because if the acid is strong then the base is weak.

Q.4.12.9: When HCl (aq) is exactly neutralised by NaOH (aq), the hydrogen ion concentration in the resulting solution is …

(1) Always less than the concentration of the hydroxide ions;

(2) Always greater than the concentration of the hydroxide ions;

(3) Always equal to the concentration of the hydroxide ions;

(4) Sometimes greater and sometimes less than the concentration of the hydroxide ions. (PKST: Q.11)

S: Always equal to the concentration of the OH^-.

(i) Description of specification knowledge (memorandum)

For a description of specification knowledge (memorandum), refer to Exhibit 4.4 above.

(ii) The student's understanding and use of concepts: Analysis and explanation

The focus in this cluster of questions and responses was to analyse the student's understanding of concentration and related terms. The questions were mostly based on the student's practical activities. In the practical work task, the student was initially asked to develop her own method for analysing acetic acid (CH_3COOH) in vinegar. At this stage, observations and an interview were conducted. The analysis was also based on the student's practical work report, in which she reported all her activities (including calculations for the analysis). The analysis followed the same pattern as the previous analyses where three areas (specification of concept, its instantiation and error prevention) were used as focus.

- Specification of a concept

The method developed by this student required that the vinegar solution be weighed. The student was subsequently asked (Q.4.12.1) whether it was possible to weigh the vinegar solution in its liquid form. According to this student, weighing was only possible if a substance was weighed in its solid form. The intention with this question (Q.4.12.1) was to determine if the student could relate this action (weighing of a liquid) to the relationship between "density", "volume" and "mass" ($d = m/v$). The student was aware (Q.4.12.2) that one needed the density in determining the mass of a solution, but could not explain its relationship to the weighing of the solution. Was this illustrative of poor organisation of her knowledge structure?

- Instantiation

In the calculation (from the report), the student could not use the density to determine the mass, and eventually the percentage, of acetic acid content of vinegar. Did the knowledge structure contribute to the student's inability to calculate the percentage content of the acid in vinegar? Her responses to Q.4.12.1 and Q.4.12.2 illustrate that the student had knowledge on density and its relationship to volume and mass. But it seems that the knowledge could not be accessed immediately owing to the way it was organised. The knowledge was stored in such a way that it made it difficult to access or use for making connections in calculations. The student could not make connections between relevant elements of her knowledge to make it useful in practical situations. However, the student did manage (Q.4.12.4) to apply the d = m/v equation in an attempt to determine the percentage concentration of the acid. This indicates an algorithmic approach to solving problems. The incorrect answer obtained could be attributed to her failure to make sense of the relationship between density, mass and volume, and eventually what percentage purity meant (as this could not be demonstrated in Q.4.12.2, Q.4.12.3 and Q.4.12.4). The student showed that she had knowledge that was not well structured and could therefore not be used in a practical situation. Connections were made but could not be used coherently to respond to new incoming information.

In Q.4.12.5, the student misconstrued the term "dilute" with "weak", and a definition of a strong acid was confused with that of a weak acid. A dilute solution, as indicated earlier, has to do with the number of moles in a given volume. A weak acid, on the other hand, is concerned with the extent of the dissociation of an acid in an aqueous solution (according to the Arrhenius concept of acids and bases). The confusion between these terms (as described above) could be attributed to the student's knowledge organisation or structure. According to Dochy (1992), the way information is stored in memory influences the manner in which it is coded. When it is activated it will affect the meaning attached to an event by an individual. In the case of this student, dilute and weak meant the same thing.

The student's response to Q.4.12.6 creates the impression that increasing the concentration of the standard solution would increase the concentration (% content of acetic acid) of the analyte (sample). The student further indicated that increasing the concentration of the standard solution would hasten the attainment of the endpoint. This statement is viable provided the concentration of the analyte remains constant, but does it suggest that one needs both titrant and analyte in *high* concentrations to reach endpoint? The confusion is understandable if one considers the student's response to Q.4.12.5. The student did not use c = n/v in her reasoning. Her knowledge (in terms of the relationship c = n/v) appears to be a misconception. In her responses, the student did not make any connection between the terms "moles", "volume" and "concentration".

In responding to Q.4.12.8 the student initially gave a correct answer on the change in the concentration of OH^- ions. But when elaborating on the reason why there was a decrease of OH^- ions when the H^+ ions increased, the student clearly did not make use of the equilibrium reaction ($H^+_{(aq)} + OH^-_{(aq)} \rightleftharpoons H_2O$) to explain her response. The response was not constructed with the three levels of chemistry's nature in mind (viewing chemistry at molecular level where ions in the solution and their reaction become the guiding light of what might be happening). The response seems to be based on the notion that the stronger the substance (acid) is, the higher the number of moles is. Stoichiometry is confused with strength. No consideration is given to the fact that the number of moles involved is what counts during titrations. It is not explicitly indicated here if strength refers to moles or extent of dissociation.

The answer to Q.4.12.6 could have been influenced or derived from the same understanding of the response to Q.4.12.8. The response to Q.4.12.9 may have been influenced by the student's familiarity with the terms neutral and equal in terms of the relationship between the OH^- ions and H^+ ions. According to Dochy (1992), individuals selectively use their prior knowledge to attend to information they are familiar with. This process occurs at a deeper level. Prior knowledge is said to fulfil a directive role in the sense that relevant information receives more attention; hence the selective attention hypothesis.

- Error prevention

Error prevention is important in the quality of knowledge being constructed. Without adequate and relevant knowledge, error prevention becomes almost impossible. It is apparent from the quality of this student's prior knowledge (as demonstrated in her responses) that error prevention was not possible. It was indicated earlier in the discussion that the student's knowledge was not well organised for better application. Error prevention is about reflection and organisation. Without well-organised and adequate knowledge, reflection becomes impossible. The conclusion here is that the student's conditional knowledge was not adequate to have prevented or detected errors. This is also the reason for the many mistakes in her responses in this cluster.

(iii) Synthesis

This cluster was about understanding the student's use of concentration in a practical situation. The student was expected to transform her declarative knowledge into procedural knowledge and at the same time using her conditional knowledge to prevent potential errors. It can be concluded that the student demonstrated her possession of declarative knowledge of some of the concepts in this cluster. But this knowledge was unrelated isolated bits of knowledge. This resulted in the student being unable to apply the knowledge to construct meaning; therefore, her attempt to respond to certain questions was not successful. The student could not use her knowledge relationally, as it was not organised in a way that it was accessible.

4.4 Summary

In this chapter, data obtained during the empirical study was interpreted and explanations provided for students' responses. Although the objective of the study was not to make any comparison between the three students, there were more commonalities than differences between the quality and usage of concepts by the three students. For example, most students managed to respond viably to questions that required declarative knowledge or specification of a concept (e.g. Q.4.11, Q.4.5.1 and Q.4.9.1). Responses to questions that required procedural knowledge or instantiation and conditional knowledge or error prevention were poorly responded to (e.g. Q.4.1.2, Q.4.5.3 and Q.4.9.2).

It is apparent also that the viability of responses as interpreted from specific elements of students' texts (concepts, meanings, thoughts, language and interpretations) was influenced not only by the quality of their prior knowledge (e.g. incompleteness in Q.4.1.3); but also by the nature, such as in Q.4.1.3 (particulate nature of matter was not used to develop a mental model of ions H^+ and OH^- in solution) of the subject matter). In some of the responses, for example, the students managed to define or specify concepts unambiguously according to explicit rules (e.g. Q.4.1.1, Q.4.5.1 and Q.4.9.1) but could not instantiate them (e.g. Q.4.1.2, Q.4.5.3 and Q.4.9.2). The students' knowledge is aptly summarised by the notion (Bransford *et al.*, 1986) that "the fact that people have acquired knowledge that is relevant to a particular situation provides no guarantee that access will occur" (p. 1080). The knowledge must be well organised for accessibility.

Incompleteness was one of the prevalent features of students' knowledge. Students with this quality of knowledge are unable to access or reflect on this type of knowledge. Incomplete knowledge is inaccessible because it is not well organised; hence it is unavailable. Most of the knowledge possessed by the three students existed as isolated bits of information in their knowledge bases. With this type of knowledge it would be difficult to construct understanding and/or generate meaning to respond viable to questions or engage productively in activities, and more specifically practical work activities (in the case of this study) that require accessibility to relevant prior knowledge.