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ABSTRACT

An investigation of Ontario high school students' understanding of acids and bases with quantitative and qualitative methods revealed misconceptions. A concept map, based on the objectives of the Chemistry Curriculum Guideline, generated multiple-choice items and interview questions. The multiple-choice test was administered to 34 grade 12 students who had completed the grade 11 advanced chemistry program. Eight of these students, from three levels of chemistry achievement (high, medium, and low), participated in 40-minute clinical interviews and follow-up interviews. Analyses of the quantitative and qualitative data revealed that the students held idiosyncratic conceptions of acids and bases which did not coincide with the concepts found in the curriculum guidelines or prescribed texts. The students in this exploratory study retained their everyday concepts of acids and bases and grasped few of the scientific concepts. More instruction time may help students to develop understanding of scientific concepts such as ions and pH. This document includes an introduction, discussions of methods and analyses, cases and concept maps, findings and a list of 39 references. Appendices include a copy of the multiple choice test, and a copy of each of the interview tasks. (Author/CW)

High School Students' Concepts of Acids and Bases

by

Bertram H. B. Ross

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in conformity with the requirements for

the degree of Master of Education

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Abstract

An investigation of Ontario high school students' understanding of acids and bases with quantitative and qualitative methods, revealed misconceptions. A concept map, based on the objectives of the Chemistry Curriculum Guideline, generated multiple-choice items and interview questions. The multiple-choice test was administered to 34 Grade 12 students, who had completed the Grade 11 advanced chemistry program. Eight of these students, from three levels of chemistry achievement (high, medium, and low) participated in 40-minute clinical interviews and follow-up interviews.

Analyses of the quantitative and qualitative data revealed that the students held idiosyncratic conceptions of acids and bases, which did not coincide with the concepts found in the curriculum guidelines, or prescribed texts.

The students in this exploratory study retained their everyday concepts of acids and bases, and grasped few of the scientific concepts. More instruction time may allow students to understand scientific concepts, such as ions and pH, which were identified as major problems. Further research with a larger sample is needed before specific recommendations can be made.

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Others have contributed indirectly to the thesis and include, Dean Paul Park, Professor John Olson, Professor Bill Peruniak, Professor Barb Mansfield, Professor Tom Russell, Professor Irwin Talesnick, Professor Skip Hills, Professor Nancy Hutchinson, Frank Cerisano, Jan Carrick, and Rose Chan. I would also take this opportunity to thank my friend Adella Gillespie for her encouragement throughout the course work and the thesis process.

To the students who participated in the study, I salute you! You were great despite the trying circumstances. This study could not have been completed without the assistance of the School Board, the Principal, and the Science Staff at the school. My thanks to you. Finally, I would thank any other persons whom I might have inadvertently excluded.

This thesis is dedicated to my wife, my son, my daughter, and the memory of my deceased father.

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Chapter 1

Introduction

The focus of this thesis is high school students' conceptions of a topic taught in all chemistry courses: acids and bases. As shown below, there is surprisingly little known of this area of students' concepts: chemistry curricula, textbooks, and teaching appear to proceed without this knowledge. Because there is no information available on students' concepts of this topic, the present study is both exploratory and clinical. It involves eight 12th-grade students, and uses quantitative and qualitative methods.

In this chapter, the primary and secondary purposes of the study are described following the statement of the problem. Next, the significance of the study is argued from two perspectives: current research on students' understandings of science concepts, and the significance of this work for designing instruction. The chapter closes with an overview of the remaining chapters.

The Problem

My interest in students' concepts of acids and bases emerged from some of my experiences in teaching chemistry. I found that new students seemed unable to grasp abstract concepts such as atomic structure, bonding, and periodicity. But once students began working with "dangerous" acids, I was able to use their interest in this topic to design a way to teach the abstract concepts which they had found to be difficult beforehand. Accordingly, acids and bases became a central part of my chemistry course.

Some might wonder why students' ideas of acids and bases are worth investigating. Indeed, the principal of the school at which data for the study were collected asked "Why all this fuss about acids and bases?" This question has been appropriately answered by Cotton and Lynch (1968):

> Acids and bases are, in fact, key chemicals in all the chemistry that occurs in water...acids and bases have "personalities" familiar (to us) from everyday experience. (p. 384)

Although acids and bases are "key chemicals," no studies have been done to determine high school students' views of them. Perhaps the constant media attention to acidic rainfall as an environmental hazard, and our dependence on antacids to provide relief from stomach complaints cause us to take students' understanding of acids and bases for granted. But, in an interview with "Letty," who had recently completed Grade 11 chemistry, I confirmed that students are sometimes overwhelmed by this topic (the interviewer's speech is italicized):

> *And do you feel that you understand much, about acids and bases?*
>
> Not an awful lot.
>
> *Did you find the topic interesting, boring, or dull?*
>
> Um kind of interesting but also hard at the same time. Kind of confusing, and yes it was interesting but [long pause]
>
> *Do you think it was confusing because you were doing . . .*
>
> It was a lot to remember.
>
> *Oh, a lot to remember.*

Letty acknowledged that she found the topic interesting and hard at the same time. Perhaps she found it hard because too much information was given. It is expected that students encounter other problems with acids and bases which will be revealed in subsequent chapters.

Purpose

The general purpose of this exploratory study is to investigate what a group of high school students understand about acids and bases. As described below, the group is drawn from a Grade 12 class of academically-oriented high school science students. The primary purpose of the study is to generate a full account of each student's concepts of acids and bases with special attention given to the inter-relationships of these concepts that reveal each student's understandings.

Because of the clinical nature of the study and its use of current curriculum guidelines and texts, it is possible to address the following secondary purposes:

1. To assess the validity of the test items that are used to evaluate students' understanding of acids and bases.
2. To explore the relationships between these students' understandings and those intended by the curriculum guidelines.
3. To assess the study's method for investigating students' concepts of acids and bases.

Significance of the Study

The significance of this study is based on two arguments: first, that the study contributes to the literature on "students' misconceptions," reviewed below; and second that the information obtained from the study is significant to the design and evaluation of instruction in acids and bases.

Student Ideas or Misconceptions in Science

Results of the research on students' ideas in science reveal the presence of many misconceptions: some are present before instruction and others arise as a result of instruction (White & Tisher, 1985). "Misconceptions" in this study refers to any knowledge or understanding that differs from scientific knowledge or understanding, acceptable at the secondary level of education. These include the phenomena of alternative frameworks (Driver & Easley, 1978), in which pupils have developed autonomous frameworks for conceptualizing their experience of the physical world, and also errors (Fisher & Lipson, 1986) which are concepts that differ from an ideal or correct model or performance.

Much research has been done on students' views in science but, as shown below, the area of acids and bases has been relatively unexplored, so the current study has the potential to contribute to the body of research in science education.

INTRODUCTION

Studies on students' conceptions have been undertaken at all levels of schooling. In an interview study of elementary-school children's conceptions of the earth, Nussbaum and Novak (1976) identified five different views, ranging from the very confused to the adult view. Two examples of the confused views expressed were "earth referred to a separate planet in the sky" and "it has a bottom somewhere past the South Pole." These elementary-school children acquired or held misconceptions about a topic that they might generally be expected to understand.

Not surprisingly, difficult topics like gravity and balancing chemical equations pose problems for students. Gunstone and White (1981) investigated first-year university physics students' notions of gravity and found the students unable to relate their knowledge to everyday phenomena, such as predicting the speed of fall for an eraser. Although students used mathematics to explain their predictions, its usage was inappropriate; and when their predictions were correct the students were unable to explain them. Similarly, in an interview study Yarroch (1985) found that many high school students who balanced chemical equations successfully, possessed very poor understanding of chemical subscripts. The results of such studies on gravity and chemical equation balancing underline the importance of probing students' understanding in other areas.

Misconceptions have also surfaced in science topics that were presumed to pose no real difficulties to students. For example, most high school students might be expected to understand the changes of state of water. Osborne and Cosgrove (1983) found some interesting viewpoints about the change of state of water when they conducted studies with students, whose ages ranged from 8 to 17 years. For instance, one of the correct explanations given for condensation was "moisture in the air has gone onto the side of the jar and turned into water," at the same time a misconception surfaced in the form "water comes through the glass by diffusion." Students with misconceptions about condensation will have problems with more difficult concepts, such as distillation, that depend on an understanding of condensation. Furthermore, water is the solvent for acids and bases (as taught at Grade 11) and its properties need to be understood for an appreciation of acids and bases.

Also, a knowledge of stoichiometry is important if students are to understand the concepts of acids and bases. Mitchell and Gunstone (1984) found students brought six misconceptions to the study of stoichiometry. Two of these misconceptions were: atoms and molecules are the same, and gases have little or no mass. In their conclusions, the researchers determined whereas chemists see chemical reactions as a re-arrangement of immutable atoms into allowable molecules, children see chemical changes as the appearance or disappearance of matter. Since these topics (water and stoichiometry) include concepts that are linked to acids and bases, it can be assumed that misconceptions are held by students about acids and bases.

A search of the literature has identified very few studies on students' concepts of acids and bases. But there is evidence that acids and bases may be a difficult topic. Burns (cited in Carr, 1984) surveyed a sample of secondary school chemistry students and found that the topic of acids and bases was perceived to be difficult.

Research information on students' concepts of acids and bases was found in only two studies. Cros et al. (1986) probed first-year university students' conceptions of the constituents of matter and their notions of acids and bases. The students were found to have a good knowledge of formal descriptive aspects, but inadequate conceptions of concrete phenomena, such as heat being released during an acid-base reaction. The students did not appear to connect their knowledge with everyday life. In a follow-up study, probing second-year university students' conceptions, Cros, Chasrette, and Fayol (1988) found some of the students had modified their concepts in the right way. For example, the usage of the scientific definition for acids (an acid releases H^+) replaced the descriptive definition (pH less than 7). Other concepts, such as, the descriptive definition used for pH (measure of acidity) had hardly changed.

These findings anticipate students' misconceptions on acids and bases. If students entered university with misconceptions about acids and bases, and these were retained after two years, it is reasonable to expect that Grade 11 students will also have some.

Factors that influence misconceptions. Factors identified as sources of students' misconceptions, include lack of prior knowledge, ordinary language usage in the classroom, and everyday language. Chandran, Treagust and Tobin (1987) identified prior knowledge as an important factor in chemistry achievement. Students lacking prior knowledge about a topic will be unable to grasp new concepts presented to them in the classroom. Also, the use of ordinary language (Munby, 1976) sometimes disguises the fact that scientific statements are intended to convey a different meaning from everyday interpretation. The findings by Cosgrove and Osborne (1983) that children have ideas about the changes of state of water that are quite different from the views of scientists support Munby's argument. In a pilot study, the present author found students new to the Grade 11 classroom, had few ideas about bases and thought that all acids were dangerous substances. The students were aware of terms like "battery acid" for sulfuric acid, and "antacids" for a collection of substances that are in fact bases, and this knowledge may have helped to promote confusion.

There may be other contributing factors to students' misconceptions, such as the use of models, and the curriculum. Carr's (1984) textbook survey revealed conflicting viewpoints and varied sequences of the models used to explain the concepts of acids and bases. Carr suggested students might be confused when the three models (Arrhenius, Lewis, and Bronsted-Lowry), are introduced in the same chemistry course. To support his claim he cited texts that switched from one model to the next to explain the same concept. Carr's argument is supported by Osborne and Cosgrove (1983) who found: "scientific models which pupils have been taught can appear to pupils to be rather abstract; hardly, if at all, relatable to everyday experience" (p. 836).

Ontario Grade 11 students are taught the Arrhenius conceptual model, in accordance with the "Ontario Ministry of Education Curriculum Guideline, Part 13, Chemistry" (Ministry of Education, Ontario, 1987). (Cited as the "Chemistry Curriculum Guideline" for the remainder of this thesis.) However other models, such as the Bronsted-Lowry model and the Lewis model, are found in the prescribed textbooks. If two or all three of the models are covered during instruction, confusion will result if the students cannot accommodate the concepts introduced by the models (Simpson and Marek 1987).

If curriculum developers are informed about the concepts students process at certain grade levels, they can include objectives and skills that are within reach of the students. Mayer (1987) proposed:

> Most science textbooks and instructional programs assume that high school and college science students are capable of scientific thinking (i.e., that the students are solidly in Piaget's formal operational period)...there is some startling evidence that some students may enter the science classroom without the prerequisite skills required for scientific thought. (p. 385)

When students are instructed on the topic of acids and bases they will gain new knowledge only if the new knowledge is linked to previously learned concepts and propositions (Novak, 1981). The present study may provide insights for curriculum and instructional planning by identifying the students' prior concepts and propositions.

Possibly, teachers may unknowingly contribute to students' misconceptions. In a study conducted with Nigerian high school teachers, Ameh and Gunstone (1988) found teachers exhibit the same range of misconceptions as has been found in students, and differed only from their students by the smaller frequency of misconceptions and their tendency to use more sophisticated science terminology to express their misconceptions. Teachers' misconceptions, their causes and effects, are beyond the scope of this study, but their presence clearly increases the probability of students' misconceptions.

Significance for Instruction

The proposed study has the potential for making an immediate contribution to teaching and evaluation in high school chemistry. Present thinking in instructional psychology about the significance of knowledge of students' conceptions to instructional planning is well represented by Reeve, Palincsar and Brown (1987), who proposed:

> The more we know about how students prefer to think and the more we know about their biases as well as their strengths, the more likely it is that we shall be able to design effective instruction tailored to their needs. (p. 127)

Another case for the importance of a knowledge of students' concepts for instruction is advanced by Cachapuz and Maskill (1987):

> an essential feature of diagnostic teaching is therefore to find out more about the various and different meanings learners have about a given content area....These private meanings are considered the base upon which teaching strategies should build. (p. 491)

The exploratory study will give important information to chemistry teachers about students' misconceptions and allow them to design instructional strategies to correct or modify misconceptions. The need to inform teaching is underscored in the Chemistry Curriculum Guideline: "The Grade 11 advanced level chemistry course is designed to provide a fundamental background that will enable students to 'understand' chemical concepts" (p. 8). If misconceptions at Grade 11 are allowed to go unchallenged they may never be altered (Simpson & Marek, 1988; Cros et al., 1986), and there is evidence for their persistence beyond the tertiary level (Ameh & Gunstone, 1988). Information from this study will allow the adoption of strategies that could transform misconceptions at an early level, will guide chemistry testing, and will enable teachers to diagnose misconceptions that students hold in other areas of Grade 11 chemistry.

Reasons for students' tendency to recall less about bases (Cros et al., 1986), and more about acids, can be derived from this study. In their study, Cros et al. determined: "students found it easy to give examples of three acids...the situation was different for bases; forty three percent of the students were unable to name more than two bases" (p. 309). Information on bases will be extremely important because, although the curriculum usually prescribes instruction to allow students to understand as much about bases as acids, there is evidence that this does not occur.

Improved instruction on acids and bases may lead to improved instruction in other areas of science. Biochemistry students need to possess an understanding of the nature of acids and bases. For instance, an understanding of enzymes is important because enzymes function in specific acid-base environments and control the steps of many synthetic reactions. Enzymes are proteins, and their amino acid units have both acidic and basic side chains (Whitman, Zinck, & Nalepa, 1982, pp.418-428). Similarly, agricultural scientists draw from a prior knowledge of acids and bases to enhance their expertise in crop cultivation.

These arguments demonstrate that the study is significant for two reasons:

1. It has potential to contribute to the research on high school students' conceptions. There has been little systematic study of these in the important area of acids and bases.
2. The results of the study can contribute to instructional planning and testing.

Overview of the Study

In chapter 2, details of the data collection methods of the present study (a multiple-choice test, concept mapping and clinical interviews) are given. Chapter 3 includes an evaluation of the quantitative instrument (a multiple-choice test), analyses of its items, and provides inferences concerning students' understanding of acids and bases. Chapter 4 consists of three case studies, and concept maps for the eight participants who are interviewed. The case studies represent the high, medium, and low achievement levels in the multiple-choice test. In chapter 5, common themes that emerged from the concept maps, the multiple-choice test analyses, and the interview protocols are presented, and conclusions made about students' understandings and misconceptions. A summary of the study, a discussion of its principal findings, and the implications for future research are found in the final chapter.

Chapter 2

Methods

This chapter describes the research methods and the sample used in the study. As noted in chapter 1, both quantitative and qualitative data were collected. A multiple-choice instrument was used to provide preliminary information about students' knowledge of concepts significant to understanding acids and bases, as proposed in the Chemistry Curriculum Guideline. Clinical interviews were designed to provide detailed information of each participant's understanding of acids and bases. The multiple-choice instrument and the clinical interviews were based on a procedure known as "concept mapping." Because concept mapping and concept maps were central to the data collection and data analysis of this thesis, the present chapter begins with a description of these. Particular attention is given to how the initial concept map (hereafter called the "model" concept map) for the test and interviews was developed. The next section "Sources of Data" is in two parts: the first describes the development of the multiple-choice instrument, and the second gives a brief description of the clinical interview. The third section describes the students who participated in the study. The fourth section, "Data Collection," describes the administration of the multiple-choice test, and gives extensive detail on the conduct of the clinical interviews. The chapter closes with an overview of the chapters describing the data analyses.

Concept Maps

Concept maps are ways of representing concepts and their interrelationships. Novak and Gowin (1984) have suggested their use for instruction because they "work to make clear to both students and teachers the small number of key ideas they must focus on for any specific learning task" (p. 15). Concept maps for instruction are constructed by writing concepts on a sheet of paper and by drawing lines among them to represent interrelationships. Concept maps have already been used in research: one can draw a subject's concept map by attending to the concepts used and the relationships among them. Nussbaum (1985) uses this approach to represent children's concepts in particle-kinctic theory, and Bloom (1989) uses the approach to depict the cognitive ecologies of elementary-school children in the context of science.

The multiple-choice instrument used in this study was derived from two sources: the items of the Ontario Assessment Instrument Pool (OAIP), and the model concept map that follows, depicting the concepts of acids and bases. (The OAIP contains a large number of items for each subject area and is designed to test objectives. This OAIP chemistry instrument has already been pre-tested and its items analyzed).

The author drew from the Chemistry Curriculum Guideline for chemistry to design the model concept map, as follows. The objectives pertinent to the learning of acids and bases were extracted and sequenced according to their level of difficulty. From those objectives, a list of concepts were made and links established between those with similar connotations. The concepts that are equally related to acids as well as bases (ions, neutralization, and oxides) were placed at the top of the model concept map (see Figure 1) with the more specific, less inclusive concepts arranged below them. The pH concept could have been positioned at the top of the model concept map, but it was more appropriate to place it in the center of the map where it connected the concepts at the bottom with the concepts at the top. When the concept map was completed, it was apparent that some concepts and relationships were not tested by the items of the OAIP for chemistry. Additional items were constructed to fill the gaps, as described in the next section. The item numbers are placed on the model concept map to indicate the concept that is tested by each item. The topics and questions introduced during the clinical interviews, described below, were also derived from the model concept map.

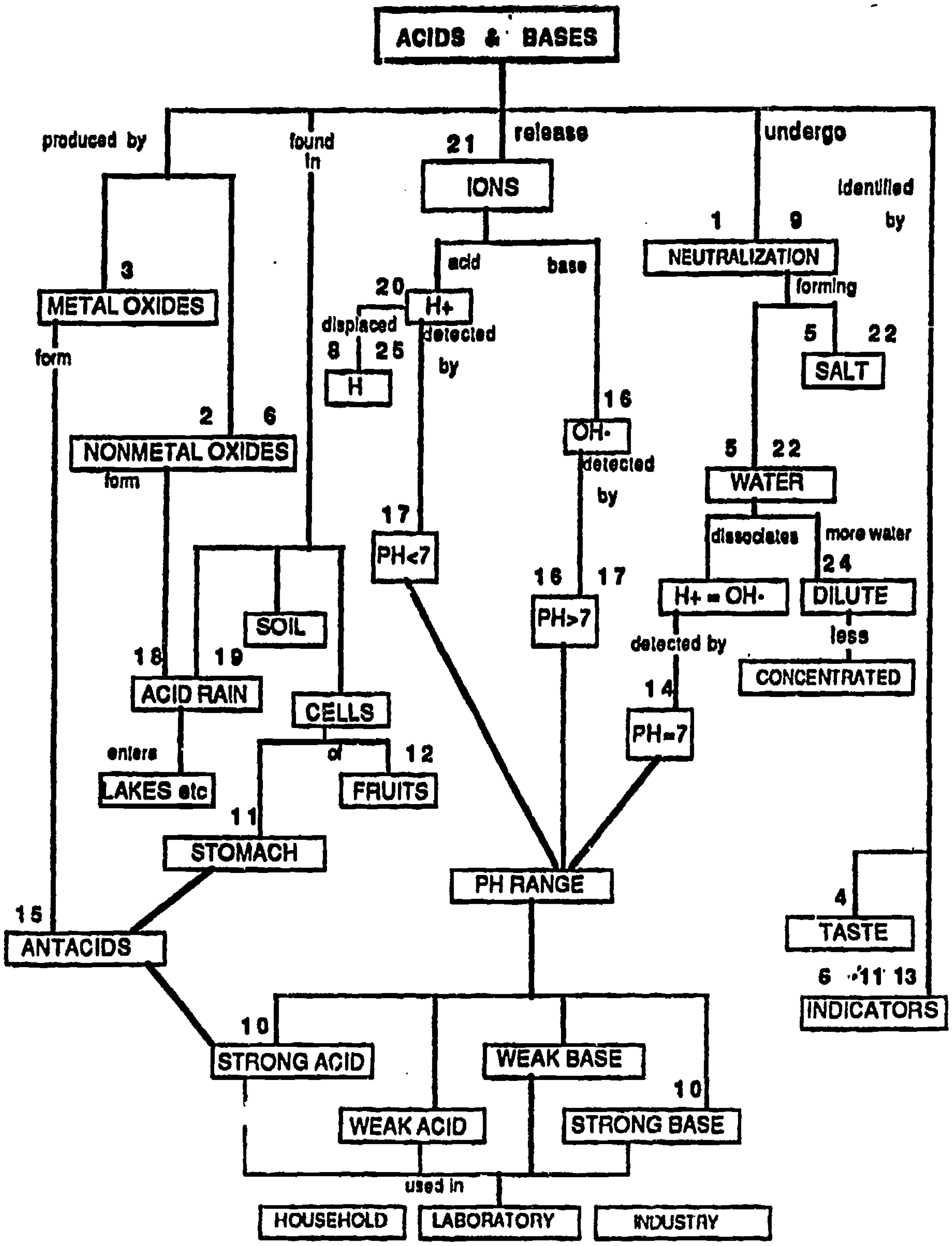

Figure 1. Model Concept Map

Sources of Data

Recently, educational researchers have shown an increased tendency to combine quantitative and qualitative methods (Mitchell & Gunstone, 1984; Cros et al., 1986). This combining of methodologies has been encouraged by Howe (1988), "Far from being incompatible, the quantitative and qualitative methods are inextricably intertwined" (p. 12). Similarly, two sources of data, a multiple-choice test, and clinical interviews, were used to determine students' understanding of acids and bases in this study.

Multiple-choice Test

As previously mentioned, the multiple-choice test used in this study (Appendix A) was derived from the model concept map and items of the OAIP. Ten of its 25 items (2-8, 14, 21, and 23) were drawn from the OAIP and the remainder, based on the objectives of the Chemistry Curriculum Guideline, were constructed by the author to test the concepts that appear on the model concept map, but are not tested by the OAIP items.

In a multiple-choice test, students' responses to the items are restricted to the answers that are provided. Each of the items used in the present study had one key and three distractors, so students' responses could reflect their knowledge only in the range provided by these four answers. Because students may have had other ideas not represented in the four answers, the clinical interview was introduced to facilitate the elicitation of students' ideas.

Clinical Interviews

The major source of data for this exploratory study was 40-minute clinical interviews, which were audio-tape recorded. Clinical interviews have been successful in probing students' understanding (Pines & Novak, 1978; Osborne & Cosgrove, 1983; Yarroch, 1985), and they are endorsed by White and Tisher (1985), who argued:

> The replacement of the interviewer by printed instructions and questions, and of oral responses and physical acts with written answers, inevitably causes loss of flexibility in questioning and in depth of insight. (p. 888)

The questions asked in the clinical interviews were based on (a) the model concept map, and (b) responses to the multiple-choice test. Further details of the clinical interviews are given below in "Collection of Data."

Participants

Thirty-four Grade 12 students, who had completed the Ontario Grade 11 advanced chemistry curriculum, wrote the multiple-choice test. ("Advanced" refers to students who are in the top level of the Ontario academic ability group.) After the test, the Grade 12 science teacher informed the eight students of their selection for the interviews, and the author explained the nature of the research. The selection of the eight participants was based on their Grade 11 chemistry performance, and on the recommendation of their teachers. Selected were: two from the top level (average 90% or more on course mark), three from the medium level (average above 80% but less than 90%) and three from the lower level of grade 11 chemistry achievement (average below 80%). (Gender did not influence selection, but students with non-English backgrounds were excluded.)

Collection of Data

After the Grade 12 science teacher explained the nature of the study, he administered the 40-minute multiple-choice test to 34 students in two of his classes. Then, he collected the answer sheets and returned them to the author who analyzed the students' answers to provide an estimate of the students' knowledge of acids and bases. This preliminary analysis allowed the author to modify questions on the clinical interviews. After the preliminary analysis of the multiple-choice test the answer sheets for the eight participants were filed until the detailed analyses (chapter 3). Their interview protocols were subsequently added to the files.

Each participant was interviewed twice: an initial structured interview, and a semi-structured follow-up interview.

The first set of clinical interviews was conducted three days after the administration of the multiple-choice test. Two clinical interviews were conducted each morning, and two each afternoon in the familiar surroundings of the school's laboratory. Each clinical interview started with a brief statement of the purpose of the research and a few warm-up exercises. Participants were presented with tasks about four aspects of acids and bases (explained below), and their responses were audio-tape recorded. During the interview, participants were encouraged to write answers or to write chemical equations to complement their verbal responses, but when they wrote they did so sparingly. Questioning elicited additional students' ideas to those obtained from the multiple-choice items, and allowed clarification of some responses to selected items on the multiple-choice test.

The follow-up interviews, designed to probe for deeper understanding and to clarify students' ideas, were conducted four weeks after the initial interviews, and were based in part on the preliminary analyses of the first interviews.

The interview tasks (see Appendix B), outlined below, were written on cards that contained stimuli in the form of drawings, diagrams, and pictures, so it was not necessary to provide the participants with concrete stimuli. Also, the participants had written the multiple-choice test three days previously, and were expected to be familiar with the topic.

The first set of tasks were modified from the "Demonstrate, Observe and Explain" method (Champagne, Klopfer & Anderson, 1985). Each participant was shown a list of materials, such as desert and forest soil, and substances commonly found in a household, such as cleaning agents, and foodstuffs. The initial intent was to ask the students to make predictions about the pH values of the substances, show them the accurate values and ask them to relate this information to how the substance was used. But, because the first participant appeared to have great difficulty recalling pH values, they were only required to classify the substances as being either acidic or basic, and to give reasons for their selection of one acidic and one basic substance.

The other tasks were based on the "Interview-about-Instances" method (Gilbert, Watts & Osborne, 1985) that has been used in investigations about physics concepts. Because chemistry concepts are investigated in the present study, appropriate modifications were made when the cards were designed. The cards showed examples of (a) the concept of strength of acids and bases (b) the concept of neutralization, and (c) acids and bases used in everyday life. The cards provided:

1. a mixture of examples and non-examples, designed to appeal to the interest of the participants (Gilbert et al., 1985), and
2. the focus for an open-ended discussion whose direction was largely determined by what the student said.

Questions posed to the students ranged from open-ended ones, which could not be answered by "yes" or "no," to those that could be answered by a simple statement of fact (Novak & Gowin, 1984). For example, when participants were presented with the reactions between magnesium ribbon and equal volumes of hydrochloric acid and acetic acid of the same concentration, they were first asked: "Why do you think bubbles of gas appeared more quickly in test tube Y (containing hydrochloric acid), than in test tube X (containing acetic acid)?" This was followed by the question: "Is acetic acid a weak acid or a strong acid?"

At the end of each clinical interview each participant was required to explain briefly his or her understanding of (a) an acid, and (b) a base. Then, during the follow-up interviews, each participant was asked to give five word associations. (Words or phrases that came in their minds when they thought of acids and bases.) Word associations have been successfully used to probe students' understanding (Cachapuz & Maskill, 1987).

Transcription. While responding, the participants were carefully observed, and notes made of gestures, faltering or irregular pausing (Gilbert et al., 1985). Attempts were also made to record the tone of voice and the duration of any pauses. Each interview was transcribed in two distinct phases (Gilbert et al., 1985). In the first phase, words and noises were transcribed. In the second phase the tape was replayed and intonations, pauses, and comments were inserted. These data were used to assess coherence of verbal responses; for example, units of articulation correspond to integrated cognitive structures, while pauses and hesitations indicate shifts in the processing of cognitive structures (Ericsson & Simon, 1984). Coherence can be an important indicator of understanding.

Overview of the Analysis

The analysis was performed in three parts: The first part concerned the quantitative data and is discussed in chapter 3. Chapter 4 presents the second part of the analyses. Here the participants' multiple-choice results and interview protocols are analyzed, and concept maps are drawn. The third part is a collective thematic analysis of the quantitative and qualitative data. This is described in chapter 5.

Chapter 3

Evaluation and Analysis of the Multiple-Choice Test

In this chapter the multiple-choice test is evaluated, and its items analyzed to give insights about the students' knowledge of acids and bases. Because two sets of items (OAIP items and author-constructed items) are included in the test, separate evaluations of each item set are included. (Information drawn from these analyses are added to the interview data for further analyses in chapters 4 and 5).

The chapter is in three parts. First, there is an evaluation of the test. Second, its items are analyzed (a) individually, and (b) collectively as OAIP items and author-constructed items. Finally, conclusions are drawn from the analyses about the students' knowledge of acids and bases.

Test Evaluation

The validity and reliability of the test will influence any conclusions made. By basing the multiple-choice test on the model concept map constructed from the objectives of the Chemistry Curriculum Guideline, its content validity was enhanced.

Thirty four students wrote the 25-item test. The total scores ranged from 7 to 19. The mean was 14.32, and the standard deviation 2.96. The reliability coefficient, calculated from Kuder-Richardson (KR-20) formula was 0.454.

A mean of 14.32 reflects an appropriately difficult test, and this is substantiated by a range (7-19) with no perfect or zero scores (Noll, Scannel, & Craig, 1979). The standard deviation (SD) of 2.96 is consistent with all the students coming from an "advanced" achievement group.

The use of the Kuder-Richardson formula to calculate the reliability coefficient was endorsed by Sax (1980) for power tests with content validity. The low reliability coefficient

(0.454) obtained is a function of the criterion-referenced nature of the test (Sax, 1980); that is, the items test different aspects of the concepts. Accordingly, the test is considered to be a reliable guide to the students' knowledge of acids and bases.

Item Analysis

The item analysis provides important information about the students' knowledge of acids and bases. By checking the students' wrong answers, it is possible to analyze their performance on the test, and to identify areas of content or objectives that have not been learned (Noll et al., 1979). The item analysis is in two parts: First, each item is analyzed to determine its discrimination index, its difficulty level, and its correlation with the total score. Then, comparisons are made between the OAIP items and the author-constructed items.

Analysis of Individual Items

In order to calculate the discrimination index (D) for each item, the scores of the students were divided into three groups: high, medium and low. The high and low groups each consisted of eight students (24% of the sample). Sax (1980) recommended 27% as ideal for large groups while Noll et al. (1979) suggested 25%. The D index for each item was obtained by counting the number of correct responses for the high and low groups, then subtracting the total correct responses for the low group from the total correct responses for the high group and dividing by eight (number of students in each group). D indices (Table 1) ranged from -0.12 to 0.67. According to the recommendations given by Sax (1980) items that discriminated from 0 to 0.20 should be revised, and items that did not discriminate should be omitted. Based on these values, items with D indices above 0.20 were seen as acceptable. Eight items failed to meet this standard (see Table 1).

The difficulty level of an item (p value) is the fraction of the number of students who answered the item correctly. Sax (1980) recommended 0.63 as an optimum p value for items with four distractors. Based on this value, items with p values from 0.4 to 0.8, were seen to be adequate. Nine items failed to meet this standard. It is appropriate to note that p indices are related to D indices because very easy and very difficult items do not usually discriminate well.

Table 1.

Analysis and Rating of Multiple-Choice Items

Item	D	p	r	Rating
1	0.12	0.853	0.068	0
2	0.37	0.588	0.318	3
3	0.37	0.235	0.414	2
4	0.37	0.324	0.419	2
5	0.00	0.529	0.044	1
6	0.25	0.324	-0.027	1
7	0.00	0.029	-0.285	0
8	0.25	0.412	0.378	3
9	0.68	0.824	0.580	2
10	0.37	0.559	0.261	3
11	-0.12	0.853	-0.068	0
12	0.25	0.735	0.318	3
13	0.12	0.706	0.182	1
14	0.50	0.735	0.341	3
15	0.37	0.824	0.474	2
16	0.67	0.588	0.420	3
17	0.50	0.647	0.419	3
18	0.00	0.471	0.232	1
19	0.00	0.971	0.019	0
20	0.37	0.618	0.398	3
21	0.50	0.412	0.214	2
22	0.67	0.588	0.322	3
23	0.67	0.412	0.378	3
24	0.67	0.500	0.320	3
25	0.12	0.618	0.149	1

The correlations of each item represent the extent to which student performance on each item varied with the total score. A correlation greater than 0.25 was considered adequate since the test is criterion-referenced. 10 items failed to satisfy this criterion.

After computing D indices, p values, and correlation coefficients, the items were given one point for each criterion satisfied, and rated on a scale from 0-3. Items which discriminated well (D > 0.20), were moderately difficult (0.4 < p < 0.8), and correlated well with the total score (r > 0.25) were rated *3* and termed "good"; items that satisfied two of the criteria just mentioned were rated *2* and termed "fair"; items satisfying one criterion only, were rated *1* and considered to be "poor"; and all others *0*, "inadequate."

According to Table 1, four items (1, 7, 11, and 19) seem inadequate. Of these, Item 1 (like Item 9) is a "forced-closed item" (Sax, 1980). The items consist of four statements from which students selected the statements most descriptive of themselves. Because students are required to give opinions all responses are considered valid. Although Items 11, and 19 seem inadequate, they were retained to provide insights into students' knowledge because of their content validity. Also, Item 7 is important because it provides evidence that students lack knowledge of ionic equations. Ionic equations are considered important because of their inclusion in the Chemistry Curriculum Guideline: "Students will be expected to: explain and give examples of the following...ionic and net ionic equations" (p. 22).

Five items (5, 6, 13, 18, and 25) are rated "poor." Except for Item 6, their deficiencies are related to their low D indices and correlation coefficients but not to their difficulty levels. Item 6 discriminates adequately, but does not satisfy the other two criteria. Item 6 is retained because it concerns metallic oxides forming acid solutions, an important concept. To answer Item 5, students require skills in balancing equations and an understanding of neutralization. Scores on Item 5 cannot be omitted from the analysis because it tests relevant concepts of acids and bases. Items 13 and 18, like Item 5, require students to transfer knowledge to a chemical equation. Item 25 tests knowledge of metals reacting with acids, yet another important concept.

Various factors may account for the items that are rated "poor" and "inadequate." For example, the more proficient students might have weaknesses in topics, such as the activity series that typically precedes instruction on acids and bases. This would cause items on these topics to appear to discriminate poorly. Similarly, items on topics that were understood by all the students would appear to be too easy while those that were misunderstood by all the students would appear difficult. Because of these and other factors, the items that rated *0* and *1* are retained in the analysis.

Validity of Author-constructed Items

The construct validity of the author-constructed items was assessed by comparing the ratings on each set of items (author-constructed and OAIP), the scores on each set of items, and the correlation between the scores. (OAIP items were 2-8, 14, 21, and 23.)

A re-examination of the quality of the items, according to the ratings in Table 1, shows that: eleven items received a rating of *3*, four were from the OAIP and seven were author-constructed; five were rated *2*, two OAIP, and three author-constructed; five items were rated *1*, two OAIP, and three author-constructed. Of the four with ratings of *0*, two were from the OAIP and two were written by the author. These results indicate that the two sets of items contained good and poor quality items. As there were three author-constructed items for every two OAIP items, the proportion of each set of items with a given rating is almost the same.

Other comparisons made between the OAIP items and the author-constructed items are given in Table 2. The correlation between the OAIP items and the author-constructed items was 0.287. This can be attributed to the author-constructed items being designed to test portions on the model concept map that were not tested by the OAIP. Although there is some overlap between the concepts that are tested by the OAIP and the concepts that are tested by the author-constructed items, there is also considerable non-overlap.

The ranges and means of the OAIP items and author-constructed items indicate students performed better on the author-constructed items. (Consideration was given to the lower number of OAIP items.) It is possible that instructional factors such as insufficient class time and the inappropriate sequence of chemistry topics (Burns, 1988) prevented the acquisition of the concepts tested by the OAIP items. Alternatively, students' prior knowledge (Novak & Gowin, 1984) may have facilitated reception of the concepts pertaining to the author-constructed items. The analysis of the subscales (see Table 3), shows that students performed appreciably better on items related to everyday phenomena than on other items. Of these items (12, 13, 14, 15, 18, and 19), only Item 14 was obtained from the OAIP.

Table 2.

A Statistical Comparison of OAIP Items and Author's Items

Factor	OAIP	Author
No. Items	10	15
Maximum	8	14
Minimum	2	5
Means	4.00	10.32
S.D.	1.537	2.128
KR-20	0.116	0.387

Although comparisons between items do not provide an abundance of evidence for the construct validity of the author's items, the evidence against construct validity has been refuted.

The low reliability coefficients of the item sets can be attributed to the small number of each set of items and the criterion-referenced nature of the items.

Students' Knowledge of Acids and Bases.

Two phases of analysis of the multiple-choice test scores led to conclusions about the students' knowledge of acids and bases. In the first phase, six subcales were constructed for the multiple-choice items and analyzed to determine their order of difficulty. In the second phase, the students' selections of answer options for each item were examined, and conclusions about student knowledge and understanding were drawn from each item.

Subscales

Subscales were made for items that tested the same concept or aspects of the same concept. The subscales emerged from the concept map and the theoretical framework underlying its construction, and represent a considerable portion of the students' conceptual framework for acids and bases. Analyses of students' performance on these subscales identified areas in which students lacked knowledge or possessed misconceptions.

The selected subscales were:

1. Base Items (1, 3, 21, and 23);
2. Neutralization Items (5, 14, 22, and 24);
3. Acid Items (4, 9, 10, 11, 17, 18);
4. Ion Items (7, 10, 14, 16, and 21);
5. pH Items (12, 13, and 16); and
6. Items about everyday phenomena (12, 13, 14, 15, 18, and 19).

Other subscales, such as indicators (6, 11, and 13) and acidic and basic (nonmetallic and metallic) oxides (2, 3, 23) can be identified, but are unnecessary because of their considerable overlap with other subscales. Information about the subscales is given in Table 3.

Table 3.

Students' Results on Selected Subscales of the Test

Subscale	No. of items	Means	% Correct
Base	4	1.91	47.75
Neutralization	4	2.35	57.50
Acid	6	3.70	61.7
Ions	5	2.35	47.0
pH	3	2.02	67.3
Phenomena	6	4.05	67.5
Total score	25	14.32	57.28

As shown in Table 3, students performed best on pH items and everyday phenomena items, but experienced difficulty with base items and ion type items. The discrepancy in performance between acid items and base items supports what Cros et al. (1986) found in their study with first year-university students. The lack of knowledge of bases may be related to Grade 11 students' exposure to acid related topics, such as acid rain. Even bases are given acid names: the word "antacids" is used for substances that are basic in nature.

Only one student gave a correct response to Item 7, reflecting one of the difficulties that the ion concept presented to students. A correct response to Item 7 required an understanding of ions and the ability to write ionic equations. Earlier, Burns (cited in Carr, 1984) found high school students had difficulties with ion concepts. It is therefore reasonable to expect that questions on bases, which require an understanding of ions, will lead to some misconceptions. It is assumed students have a knowledge of ions when pH and neutralization are taught because, typically ions are introduced when ionic bonding is taught in the introductory stages of chemistry. Students' problems with ions may cause misconceptions to surface in these areas. (Correct responses to the multiple choice test are in Table 4.)

Interpretation of selection of response options

An approximation of students' conceptions is possible by comparing the frequency of responses given for each distractor (Sax, 1980). Often, an unusually large number of responses to an incorrect distractor may indicate miskeying or the presence of students' misconceptions. For this reason, any item with an unusually large number of responses to an incorrect distractor was carefully checked. Also, an item with responses equally distributed to all distractors may indicate guessing, which occurs when students do not possess relevant information in their working memories (Mayer, 1987). Evidence for misconceptions and guessing were found, but there were no instances of miskeying.

Responses to each item were examined to determine why incorrect answers were given. First the difficulty level was noted, then the number of incorrect responses was computed and subsequently analyzed. For example, Items 12 had 25 correct responses, the distractors A and C were ignored, and nine persons responded with D. Consequently, it was assumed that the nine persons had misconceptions about pH and that A and C were inadequate as distractors. The unusual number of incorrect responses to Item 7 led to a re-examination of the item. Since the question had content validity and required recall, the unusual number of incorrect responses was assumed to be due to lack of appropriate knowledge.

Similarly, conclusions about incorrect responses can be made for each of the items. The conclusions are presented, in abbreviated form in Table 5. Here it is particularly evident that students lacked knowledge of some of the concepts related to acids and bases. For example, Items

Table 4.

Summary of the Selection of Multiple-Choice Options

Item No.	A	B	C	D
1	2	29	2	0
2	20	2	7	2
3	8	15	2	6
4	14	2	11	7
5	18	2	6	8
6	11	8	9	3
7	1	1	1	31
8	14	5	14	1
9	4	28	1	1
10	19	7	4	2
11	1	29	4	0
12	0	25	0	9
13	1	5	4	24
14	2	6	25	0
15	4	28	1	1
16	8	2	4	20
17	5	22	7	0
18	3	3	8	16
19	1	0	33	0
20	1	5	5	22
21	5	6	5	15
22	3	3	20	7
23	6	15	3	10
24	11	4	17	2
25	8	1	20	5

Note: The correct response is underlined.

4, 13, 17, and 23 required recall about colors given by indicators in the presence of acid and base solutions, but less than half of the students responded correctly to Items 4 and 23, and a substantial number answered Items 17 and 13 incorrectly.

Prior knowledge about ions is necessary to answer Items 7, 10, 14, and 16. Thirty-three students were unable to identify the correct ionic equation for a neutralization reaction, given in Item 7. The seven students who chose (B) for Item 10 (strong bases produce most H^+ ions) clearly do not understand the nature of hydrogen ions. Similarly, the six students who chose (B) for Item 14 (a basic solution contains an equal number of hydrogen ions and hydroxide ions) do not understand the nature of ions. In Item 16, eight students thought that a solution with a pH of 10 was acidic, and four students thought the same solution was neutral. The misconceptions that surface in Items 14 and 16 can be attributed to a lack of understanding about hydrogen and hydroxide ions.

Also, some students seemed to have problems with Items 2 and 3 which required knowledge that metallic and nonmetallic oxides react with water to produce bases and acids, respectively. No clear pattern emerged but about half of the students gave incorrect answers. Item 2 concerned the formation of acidic solutions from water and nonmetallic oxides and 11 students incorrectly chose metallic oxides as answers. Three students did not answer. And, for Item 3, 23 students incorrectly chose nonmetallic oxides as producers of basic solutions.

Items 5, 7, 18, and 22 required an ability to balance equations, to interpret equations, and to transfer information from equations. The options selected by students for these questions suggest that although some students mastered the algorithm for balancing equations, they did not understand what was being done. (Further evidence of this is found in the qualitative analysis reported in chapters 4 and 5.) Students' problems with formulae and equation balancing may explain why, for Item 25, eight students thought chlorine gas was displaced when magnesium reacted with hydrochloric acid.

Most significantly, Items 11, 15, and 19 (which were about everyday phenomena) seemed to be least difficult. Twenty-nine correct responses were given for Item 11, 28 correct responses were given for Item 15, and 33 correct responses were given for Item 19. Item 11, although about indicators, could have been answered if students knew that acid conditions were present in the

Table 5.

Conclusions drawn by Analyzing the Options selected by Students

Item no.	Conclusion
1	Two students have non-conventional ideas of bases.
2	Lack knowledge of symbols; problems with oxides.
3	Possible, P interpreted as symbol for potassium?
4	Poor recall of indicator colors.
5	Some do not understand neutralization, nor equations.
6	None possible.
7	Lack knowledge about net ionic equations.
8	Misconception. Reaction seen as equilibrium.
9	Misconception, all acids perceived as dangerous.
10	Lack of knowledge about hydrogen ions in compounds
11	No valid information.
12	Misconception about pH. Lower pH seen as less acidic.
13	Same as for Item 4
14	Misconception. Bases are neutral.
15	Most students know about antacids.
16	Misconception, wrong proposition about pH and acids.
17	Same as for Items 4 and 13.
18	Acid rain not transferred to chemical equations.
19	Students know about effects of acid rain.
20	Activity series; source of misconceptions.
21	Same as for Item 7. Deficient knowledge about ions.
22	Some students unfamiliar with formulae.
23	Same as for Items 4, 13 and 17.
24	Complex question. Many possibilities.
25	Misconception, chlorine displaced from HCl.

stomach. Item 15 was about the nature of antacids, while Item 19 concerned the dangerous effects of acid rain. Students readily retrieved information on concepts about everyday phenomena that were related to their personal health.

Not only did students lack knowledge about aspects of acids and bases, and retrieve information about everyday phenomena readily, but some were found to possess concepts not present on the model concept map. These included: Item 1, bases are harmless; Item 9, acids are dangerous; and Item 14, bases are neutral. However, such misconceptions were not confined to weaker students nor to any subscale. For example, although pH items (Table 2) seem to be relatively simple, an analysis of Item 12 provides evidence of misconceptions about pH.

Summary

The multiple-choice test used in this study is found to be an adequately reliable and valid measure of the students' concepts of acids and bases, so it is considered to be an appropriate source of information about students' views on acids and bases. Students performed well on the items about everyday phenomena, and poorly on those items about ions and bases. Misconceptions about ions, bases, and pH, and about the reactions between acids and metals also appeared during the analyses. This information, extracted from the analyses of subscales and individual items, guided the analyses of the clinical interviews in chapters 4 and 5.

Chapter 4

Cases and Concept Maps

This chapter presents case studies and concept maps for three participants who were chosen from different levels of achievement in the multiple-choice test: Atlas from the high level, Ishmael from the medium level, and Letty from the low level. The three participants attend a secondary school in Ontario and have successfully completed Grade 11 chemistry. By presenting case studies for the participants at three levels of achievement, detailed information about the three participants' understanding and an overview of the eight participants' understanding is obtained.

Each case study consists of the participant's concept map, and a description of the participant's understanding of the concepts of acids and bases. The descriptions of their understanding are accompanied by references from the interviews. In the references the interviewer's speech is italicized, but not the participant's views. A notation is used to indicate the length of the participants' pauses. For example, ..[6].. refers to a six second pause.

Concept maps and brief descriptions are presented for the other five participants: Crista, Mabel, Delvin, Magnus, and Curly. (All the participants' names are fictitious.) The details for the design of the participants' concept maps follow.

Construction of Concept Maps

The author drew from the objectives of the Chemistry Curriculum Guideline to obtain the list of relevant concepts; these concepts are linked together (described in chapter 2) to form the model concept map, Figure 1. The concept map for each student was designed by subtracting concepts and propositions not revealed by the participants' interview protocols nor by their answers to the multiple-choice test, from the model concept map. The subtraction of concepts from the model concept map was seen as the most reliable method for concept map construction without making excessive assumptions about the nature of the students' knowledge. The concept maps (Figures 2-9) were obtained after the author examined each participant's multiple-choice answers and interview protocol, then deleted the missing concepts from the model concept map and made new linkages to represent misconceptions. Asterisks are used to indicate the participants' misconceptions on their concept maps. The concept maps were designed in three phases. In the first phase, the multiple-choice answers were scrutinized for the absence of acid-base concepts, or misconceptions. An absent concept was identified when the participant gave an incorrect answer to items that required recall (Items 4, 10, 13, 14, 17, 19, and 23). Because each multiple-choice item had been clearly marked on the model concept map, the author was able to subtract the absent concepts and produce a tentative concept map for each participant. These tentative concept maps were restructured after the analysis of the interviews.

In the second phase of the construction of the concept maps, answers to items that did not require recall, but required an understanding of one or more of the concepts of acids and bases were examined for misconceptions. When misconceptions appeared, their confirmation was delayed until the analysis of the interviews. This is because what appeared to be a misconception may have been the absence of a concept or a lapse on the part of the participant. The interviews allowed for deeper probing to determine if misconceptions existed. A misconception is present only if the student possesses the appropriate concepts in working memory, and is unable to make the correct linkages between the concepts (Novak, & Gowin, 1984; Mayer, 1987).

In the final phase of constructing each map, the first and follow-up interviews were analyzed in a similar manner to the multiple-choice test. When students gave inappropriate answers or failed to answer items that required recall during the first interview, missing concepts were identified. Inappropriate responses to questions that required understanding or linkage between concepts were identified as misconceptions. Analyses of the first interview were compared with the quantitative analyses to determine if the missing concepts had prevailed or if the misconceptions had been modified. Finally, analyses of follow-up interviews were compared with analyses the first interviews.

Case Studies

Case studies are presented to provide detailed information about each participant's knowledge and understanding of acids and bases. The three case studies presented are of participants selected from each of three levels of student achievement in the multiple-choice test: high, medium, and low. Atlas obtained the best score on the multiple-choice test and was selected from the high level. Ishmael was chosen from the medium level because of his interesting interview protocol. Letty who obtained the the lowest score of all the participants was selected from the low level. Each case is described in five phases. The participant's concept map is first presented followed by a discussion of the participant's understanding of everyday acid-base phenomena, in the second phase. In the third phase is a discussion of the participant's knowledge and understanding of the concepts on the model concept map and their related concepts. Then, there is an analysis of the participant's explanation and word associations for an acid and for a base, in the fourth phase. Finally, a list of the participant's misconceptions with the supporting evidence is given.

The Case of Atlas

Atlas is presently in Grade 12, and ranks among the top students in his class. According to Atlas, he will pursue some science career but his plans are not yet finalized. He obtained the highest score on the multiple-choice test, *19*. Of the six items answered incorrectly, five were OAIP items. The other item (author-constructed) was not attempted because, as Atlas explained, he had overlooked it. Atlas was cooperative, as were his classmates, and he tended to give fuller responses than them. His concept map is presented in Figure 2.

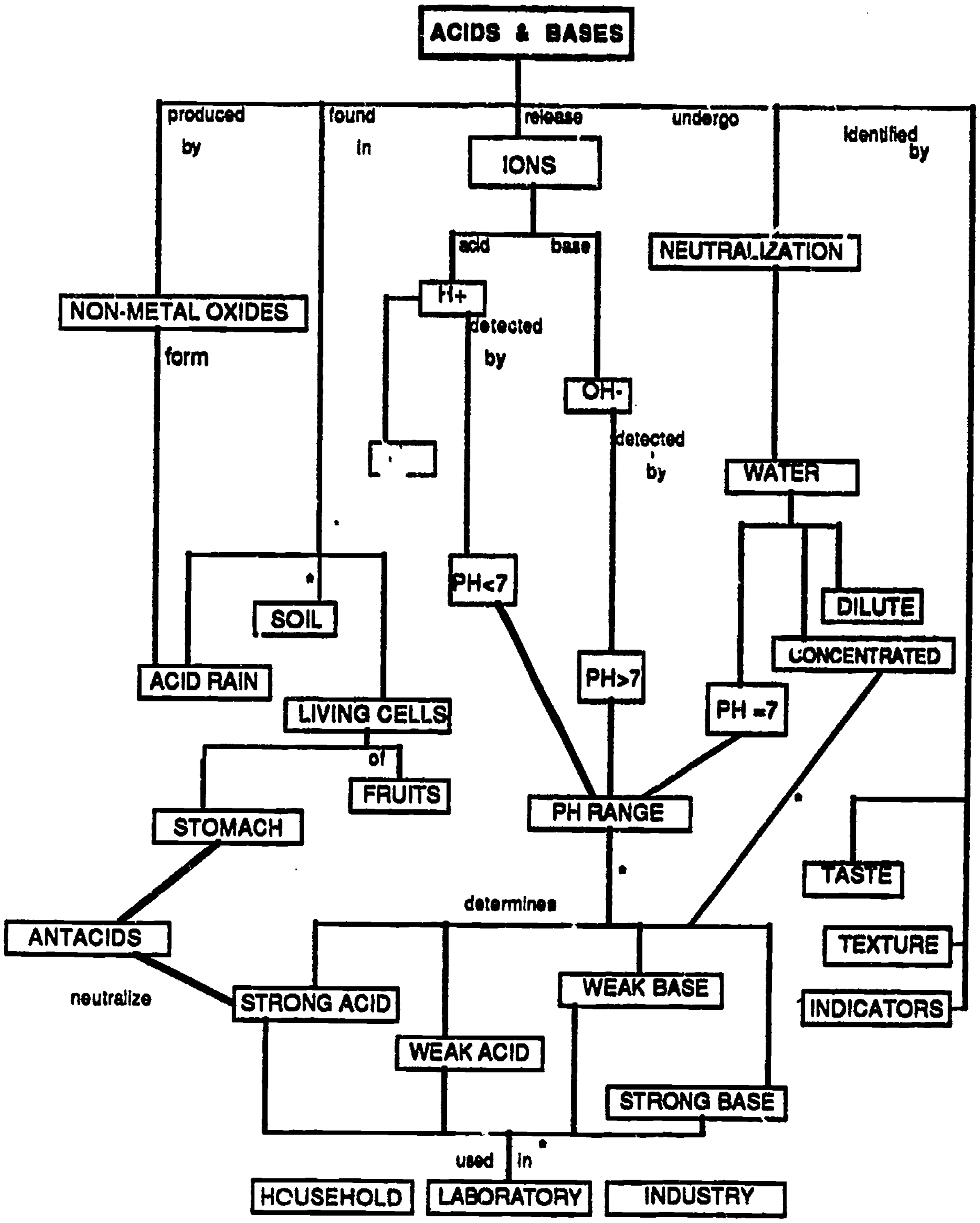

Figure 2. Atlas' Concept Map

Everyday Phenomena

Atlas correctly answered the multiple-choice items on everyday phenomena. But, questioning elicited additional information about his conceptions of everyday phenomena that were not available from the multiple-choice test. During the first interview, he was given a list of certain substances found in and around the home, and questioned about their acidic and basic nature. These substances are found in Table 6 appropriately classified as basic and acidic.

Table 6.

Correct Classification for Substances shown to Participants

Acidic	Basic
Saniflush	Bleach
Tomatoes	Ammonia
Vinegar	Washing Soda
Soft drinks	Milk of Magnesia
Lemon juice	Toothpaste
Tomatoes	Baking Soda
Coffee	Desert Soil
Tea	
Milk	
Forest Soil	

Atlas incorrectly included bleach and ammonia as examples of acidic substances; and he wrongly classified forest soil, coffee, tea, and milk as basic. His explanation for choosing bleach and ammonia as acids follows:

> OK, bleach, I will put there because..[6]..bleach I know is. What it is used to do? For taking out stains, just the basic household use, taking out stains.
>
> *What about ammonia?*
>
> Ammonia, now ammonia is sort of like. I guess I was not sure what ammonia is. Some kind of cleaning agent as I understand it, and it's strong sort of like a disinfectant which would be more like an acid.

His explanations for his choices of ammonia and bleach as acidic substances give an insight to his classification of coffee, milk, and tea as bases. His perception of a base as a safe substance for consumption would not allow him to accept a "cleaning agent," or a "stain remover," as a base.

Asked whether he had heard of "battery acid," Atlas affirmed that he had, but he was not familiar with its chemical name.

> *And what chemical in the battery allows this?*
>
> It would be an acid.
>
> *Can you tell me what acid? What is the the name of the acid?*
>
> I can't.

Atlas' explanation of acid rain was purely descriptive without any knowledge of the chemical concepts involved.

> As I understand it, the gases are emitted from the factories in the form of smoke and that generally smoke um smoke goes into the atmosphere and then it gets into um it is picked up enters in the rain. When the rain, when the water is collected in the clouds, whatever, it um picks the acids and stuff they collect with the water and when the rain comes down it brings with it the acid. It falls into the lakes and into trees and stuff and they go along with the water and take these acids into the systems.

Asked to name the gases emitted from smokestacks, he mentioned carbon monoxide as one of the gases. This is incorrect because carbon monoxide does not form any of the acids found in acidic rainfall. The oxides of sulfur and nitrogen are responsible for its formation. The topic of acid rain was re-introduced during the follow-up interview. Now, Atlas predicted that sulfuric acid would be a constituent of acid rain but he could not explain why he had mentioned carbon monoxide in the first interview.

You said carbon monoxide gas. Were you predicting this acid (sulfuric acid) from that?

From carbon monoxide. No..[10]..um..[16]..no.

What gas do you think would be in sulfuric acid?

Oh..[8]..Oh yes, sulfur oxide.

The follow-up interview allowed Atlas to retrieve more information about acid rain formation. Atlas seemed to have an adequate knowledge of "acid stomach." Referring to it as heartburn, he said it was neutralized by antacids such as Alka-Seltzer, Tums, and Milk of Magnesia.

Acid-Base Concepts

Two different sets of concepts are discussed in this section. In the first set are the concepts that facilitate students' understanding of the concepts on the model concept map. These are collectively discussed as formulae and equations; and chemical reactions and the activity series. In the second set are the concepts that are found on the model concept map: Neutralization, pH and indicators, strength and concentration, and ions.

Formulae and Equations. Atlas recognized the formulae shown on the cards during the first interview although he did not recall the formula for a well-known acid like sulfuric acid. He seemed to experience difficulties when writing equations, which is one of the skills required of chemistry students. During the first interview, Atlas was able to complete a simple neutralization equation when given the reactants, but he chose an incorrect answer to Item 5 and ignored Item 18. Both items required a knowledge of equation writing and balancing. When Atlas was allowed to check his answer to Item 5 during the first interview, he was unable to produce the correct answer. Item 7, which concerned ionic equations, was also incorrect and this may be explained as an inability to write and balance ionic equations.

Chemical Reactions and the Activity Series. The Chemistry Curriculum Guideline requires students to know about metals and the activity series. Atlas' knowledge of the reactions with metals and acids is extensive, but he said he used the periodic table to help him predict the reactions of metals rather than the activity series. I asked him to name other metals that reacted with dilute acids in a similar way to magnesium.

> OK,..[3]..lithium, potassium, um..[6]..dilute hydrochloric acid OK
>
> (he continued)
>
> Right um ..[8]... I think dilute. I dunno, lead maybe, I don't know if maybe iron would. Dilute it is something stronger but I..[4]..think zinc maybe.

I showed him this list during the follow-up interview:

> Li, K, Ca, Na, Mg, Al, Zn, Fe, Pb, Hg, Ag, Au.

Then I asked him to identify the metals that react with dilute hydrochloric acid.

> Yes, yes, I am trying to recall if I know the reaction. Magnesium yes, um sodium I think, lithium potassium, is this calcium?
>
> *Calcium yes.*
>
> Calcium and sodium and magnesium, lithium.
>
> *How do you know that they would?*
>
> Well, I know some of them from experiments we did. Just that some are reactive and in different groups of families they are more reactive than others, and so I am trying to remember which ones are more reactive. But I know the lithium potassium etc. family, and the magnesium.
>
> *What about these over there?*
>
> I don't think I know these ones. This is aluminum?
>
> *No. This um should be Ag, silver.*
>
> I don't think that the gold and the silver and mercury will, no.
>
> *Why not?*
>
> They are more stable, more stable metals than the others.

Neutralization. Neutralization is an important concept (as shown on the model concept map) especially because acids react with bases during this reaction. Quantitative analyses of the multiple-choice test show that neutralization was a moderately difficult subscale. Of the five items about neutralization (5, 7, 14, 22 and 24), only Item 5 was answered incorrectly by Atlas. The reason for his incorrect answer has been discussed already (he had problems with equations). The interviews revealed another problem that Atlas encountered with the concept of neutralization. Although he knew that acids and bases reacted during neutralization with water as one of the two products, neither Atlas nor any of the other participants verbalized a salt as the other product of neutralization. Below, I ask Atlas numerous questions about the products of neutralization, trying to elicit "salt."

> *OK, now we are going to mix what you have identified as as an acid and a base and we are going to get a compound C, what type of substance is C?*
>
> A neutral substance because the pH is seven which is a neutral number.
>
> *And the temperature of C? What is significant about the C, when you look at the temperatures of A and B?*
>
> It means that there a reaction has occurred, that the acid and the base have reacted to create the neutral substance.
>
> *Is there anything significant about the pH of C?*
>
> That it is a neutral substance.
>
> *What type of substance is potassium chloride?*
>
> Um, I think it is a solid.

Atlas did not seem to know about salts.

pH and Indicators. Typically, pH and indicator concepts are introduced early during instruction of acids and bases and are not expected to pose problems for students. If the number of correct answers given by Atlas (all except one of the pH and indicator items were correctly answered) were any indication of his knowledge of pH and indicators, he has a near perfect knowledge. But, during the interviews his answers revealed there was not much depth to his knowledge. He used what Cros et al., (1988) termed a descriptive definition for pH.

What do you understand by the term pH.

Um the level of acidity in the substance.

And the pH measures it? The pH is the measure of the level of acidity?

That's right.

According to Whitman et al. (1988), the mathematical definition of pH is: "the negative logarithm of the molar concentration of the hydronium ion" (p. 401). Atlas did not use the mathematical (scientific) definition, but used an incomplete descriptive definition saying that pH measured the acidity level of a substance. A complete descriptive definition would have alluded to the use of pH to measure the level as basicity, as well. It may be Atlas did not use the mathematical definition because it is confusing. Although the presence of hydronium ions as the only positive ion confirms the presence of an acid, and pH is the negative logarithm of the molar concentration of the hydronium ion, pH is also used to verify the presence of bases.

The item which Atlas incorrectly answered concerned the colors given by litmus paper in acidic and basic solutions. This is not seen as a serious problem but there are some implications for the students' laboratory work.

Strength and Concentration. The concepts of acid and base strength, and the concepts of concentrated and dilute solutions are shown on the model concept map. There is a difference between a strong acid and a concentrated acid. While a strong acid almost completely dissociates into its ions, a weak acid barely dissociates into its ions. A concentrated acid contains a smaller quantity of solvent (water is the solvent mentioned at Grade 11) or more of the acid dissolved in the solvent. On the other hand a dilute acid has more solvent and less dissolved acid. Atlas showed his understanding of concentration by correctly answering Item 24, and giving appropriate responses to the relevant tasks during the interview. When Atlas was asked why magnesium reacted more readily with hydrochloric acid than with acetic acid acid he replied:

> Could be the magnesium reacts more strongly with the acid in one test tube than the other because it's a stronger acid.

When I probed deeper, Atlas gave an explanation that could only have been based on some previous knowledge. He suggested that it was the composition of the hydrochloric acid that determined its faster reaction.

> Could be that I wouldn't know in which one but that the acid reacts with, I mean that the magnesium reacts with one of the acids more than the other just due to the composition of the acids and not necessarily the strength of the acids.
>
> *Say that again I'm sorry.*
>
> It could be due to the composition of the acid instead of the strength like maybe one is not more strong. OK it's just the way it reacts with magnesium. Like some different substance may cause some different reaction it's just that magnesium reacts with hydrochloric acid more strongly than I mean more violently or quickly than it does with acetic.

Although the composition of the acid influences its ability to dissociate and thus its strength, the explanation is scientifically unacceptable because Atlas seems to ignore strength as a factor in the reaction. Hydrochloric acid dissociates almost completely into H^+ and Cl^-, therefore magnesium replaces almost all of the hydrogen ions. On the other hand, acetic acid dissociates only slightly and its reaction is less vigorous. The dissociation of its ions is what determines the reactions of an acid. Atlas' ability to reason led to a misconception. I continued this line of questioning, and Atlas then, wrongly used his knowledge of atomic structure to explain why hydrochloric acid reacted with more substances than acetic acid.

> *Do you know the exact reason why or part of the reason why hydrochloric acid tends to react with more substances than acetic acid?*
>
> Probably it is a more unstable acid. As far as would be my guess.
>
> *Unstable in terms of what?*
>
> It's um, it wants to react more because of the atomic structure whether it be atoms or the electrons one of one of the or it may react more readily than the acetic acid.

Instead of making references to atomic structure, Atlas needed to refer to the dissociation of the acids into their constituent ions.

Ions. Three of the questions on ions concerned Atlas' conception of a hydrogen ion, a hydroxide ion, and their relationship to each other and to pH.

> *What type of substances contain H^+?*
>
> Um often an acid will.
>
> *An acid will. OK what types of substances contain OH^-.*
>
> Will be a base.
>
> *Base. How are H^+, hydrogen ion, and OH^-, hydroxide ion related to pH?*
>
> Um the higher (pause) the substances which contain more OH^- or generally were related to OH^- will have a higher pH number, while the greater H^+ will have a lower pH number.

His explanations for the hydrogen ion and the hydroxide ion are acceptable, and reveal an understanding of ions and their connection to pH.

Like most of the other students, Atlas incorrectly answered Item 7 which required an understanding of ionic and net ionic equations. Also, Atlas had disclaimed any knowledge of ionic equations and net ionic equations during the first interview, although they are included in the objectives of the Chemistry Curriculum Guideline. His inability to use ionic equations may hinder him from transferring information from ionic equations to other situations (Yarroch, 1985).

Understanding of Acids and Bases

Atlas' performance on the multiple-choice test (19 out of 25) suggests that he grasped most of the concepts about acids and bases. The excerpts from the interview below substantiate this to some extent. Atlas used a combination of everyday and scientific concepts when he was asked to explain what are acids. (Scientific concepts are those accepted by experts and written in textbooks. Everyday concepts are ordinary expressions that are not acceptable as definitions or properties.)

> Um an acid is a substance which..[3]..which..[10]..a reactive substance um which has the tendency to react strongly which has the tendency to react with substances..[80].. Goodness.
>
> *Take your time, how would you tell them to identify the acid what techniques would you use to identify an acid?*
>
> Well if they could find the pH level, I would say a substance with a low pH level is an acid, it often contains hydrogen ions.
>
> *Suppose they they just wanted a quick test.*
>
> You mean it has um..[3]..a bitter taste it's like sour.

Towards the end of the follow-up interview, I asked Atlas to mention words and phrases that came to his mind when he thought of acids and bases. For his word associations (as they are called) Atlas used: "reactive," "can be dangerous," "hydrochloric," "pH," and "common." In light of his explanations and word associations, Atlas has shown a reasonable knowledge of what an acid is. He mentioned pH, hydrogen ions, sour taste and a name, hydrochloric acid. By mentioning these, Atlas showed his knowledge of the scientific concepts, but his use of "dangerous," and "reactive," showed he retained some everyday concepts.

Atlas identified bases by their formulae and claimed to know a lot of them, then said he did not know them well.

> *Can you name some bases which are used in the chemistry laboratory?*
>
> Some bases Um..[10]..I know a lot of bases; they contain hydroxides. These it's more of a I don't know them well but...

However, when he was asked to give an explanation for a base he showed an adequate knowledge of bases.

> A base is a substance which has a high pH and will combine with an acid to neutralize it because it has hydroxide which will neutralize when reacted with. The hydroxide and hydrogen when reacted will form water which is a neutral substance.

Later, when I asked Atlas to use words he associated with bases, he wrote: "slippery to the touch," "opposite to acid is hydroxide," "less known about them," "pH," "can be dangerous too." Despite his claims that less is known about bases, Atlas' explanation shows he links pH to bases, knows of the hydroxide ion, and understands neutralization. These are all scientific concepts. His association of "slippery" with bases is another example of his everyday concepts.

Misconceptions

Summarized below are Atlas' misconceptions, with evidence selected from the data.

1. Bases are not used as disinfectants (i.e., bases are harmless). Atlas classified bleach and ammonia as acids.

2. Plants don't grow in an acid environment.

   > Oh, I see well I figured that the soil was. One is sand desert soil is basically sand or very dry dirt and the reason they (plants) wouldn't grow, it has to do with the nutrients in them. In desert soil there is a lot of nutrients but a lack of water um forest soil the growing would be just the abundance of nutrients. Now I mean to place them under acids or bases is um just to me they seem more fitting under bases because under acids it's more unlikely for something to grow in an acid in the case of forest or desert soil. I think it can't grow in desert soil so I put them under bases.

   Clearly Atlas' misconception about the nature of bases has prevented him from appreciating that the nutrients (ions) in the soil can contribute to its acidity.

3. The composition, not the strength, influences the reactions of acids.

   > Could be that I wouldn't know in which one but that the acid reacts with, I mean that the magnesium reacts with one of the acids more than the other just due to the composition of the acids and not necessarily the strength of the acids.

4. The pH of acids is the opposite of the pH of bases.

   > *So opposite of acid is what makes it a base? Do you think bases are opposites of acids?*
   >
   > Well their pH levels.

Conclusions about Atlas' Knowledge.

Atlas' performance on the multiple-choice test indicates he has grasped most of the concepts of acids and bases. His interview protocol reveals difficulties with equations and misconceptions about the acidic and basic substances used in the household, and about the strength of acids and bases. In light of the data, it is plausible to conclude that Atlas grasped most of the everyday and scientific concepts but did not posses all the linkages between the concept of ions and the other concepts on his concept map. These linkages are necessary for a fuller understanding of the topic.

The Case of Ishmael

Ishmael, like Atlas, is presently in Grade 12 having completed Grade 11 chemistry at the advanced level. Ishmael's performance on the multiple-choice test placed him at the medium level of achievement. Ishmael was selected because of his interesting interview protocol which showed evidence for his misconceptions being modified in the correct way. Of the 13 items he answered correctly, 2 were from the OAIP, and 11 were author-constructed. Ishmael's concept map is presented in Figure 3.

Everyday Phenomena

Of the five everyday items, only Item 18 was incorrect. Like Atlas, Ishmael incorrectly classified ammonia and bleach as acidic, and milk, coffee, tea, and forest soil as basic.

> Toothpaste a base, milk of magnesia a base, um baking soda a base, vinegar an acid, washing soda a base, um ammonia an acid, milk a base, bleach an acid, saniflush an acid apple is an acid, soft drinks an acid, um tomatoes an acid, coffee and tea a base, lemon juice an acid, um desert soil a base, forest soil basic.

When I asked Ishmael about antacids he showed he was capable of applying his knowledge of chemistry concepts to everyday situations, by including the neutralizing action of antacids in his explanation.

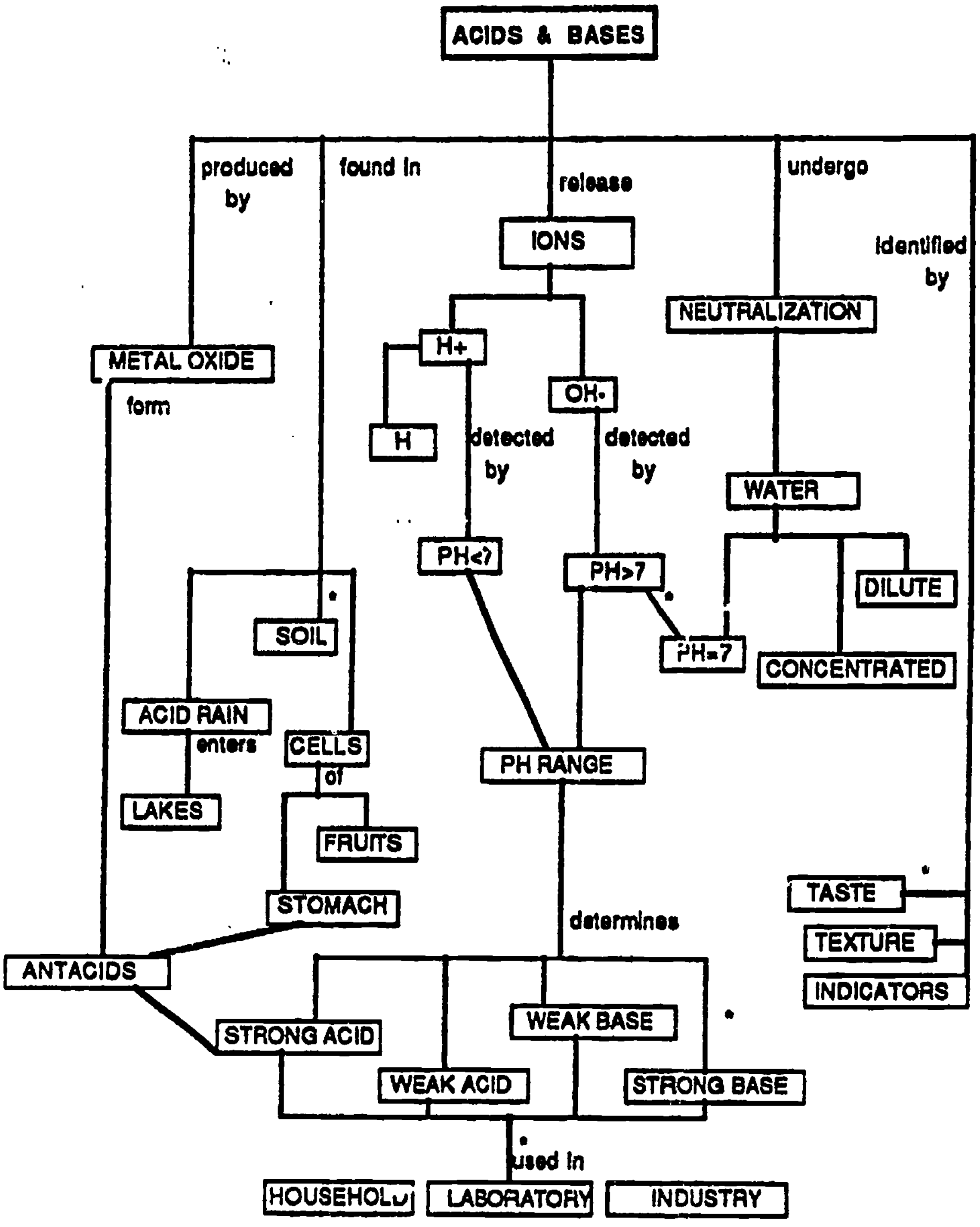

Figure 3. Ishmael's Concept Map

Um only it's basic and it neutralizes the acid in the stomach.

No chemical name was given for "battery acid" but Ishmael was familiar with the everyday name. Interestingly, Ishmael revealed a misconception about ions when he said that ions carried the current from the battery.

His understanding of acid rain was limited to the descriptive aspects. Evidence for this was shown by his incorrect answer to Item 18. He suggested that nitric acid is not one of the acids found in acid rain. Ishmael was asked to name two gases that are formed from fossil fuels and eventually form acid rain,

Oh carbon and..[10]..sulfur dioxide? [looking at the legend]

Any other gas?

I dunno carbon?

Any other?

Hydrogen.

"Carbon" is incorrect, and Ishmael's answer suggests a misconception about combustion. A student who understands combustion would name an oxide since oxygen combines with other substances to form oxides during combustion. Ishmael only mentioned sulfur dioxide because he saw it in the legend. Neither carbon nor hydrogen will react with water to form an acid. Or perhaps Ishmael answered without reflecting on the question or without thinking that he could apply chemistry concepts to something like acid rain.

Acid-Base Concepts

Below, some of the concepts that are relevant to an understanding of acids and bases are reviewed in the light of Ishmael's responses to the multiple-choice test items and his interview protocol.

Formulae and Equations. Ishmael provided competent answers to items about formulae, but items about equations posed some problems. Evidence for Ishmael's problems with equations is shown by his incorrect responses to Items 5, 7 and 18. However, in the first interview Ishmael was able to complete a neutralization equation when he was given the reactants. The ability to complete equations when given the reactants allowed him to deduce the products of other reactions. For example, although he was unable to predict the substance that was formed when a metal oxide reacted with water, he was able to do so when he wrote the equation.

Chemical Reactions and Activity Series. Ishmael knew the names of some metals that react with acids, but did not use the activity series to obtain this information.

> *Can you name any other metals like magnesium that react, that would react with X and Y the same way.*
>
> Um, lithium.
>
> *Any others?*
>
> Sodium
>
> *Any others?*
>
> Um, no.

Neutralization. Of the five items about neutralization, Items 5 and 14 were answered incorrectly. Ishmael's answer to Item 14 incorrectly suggested that a base is one of the products of neutralization. However, during the first interview he showed a better grasp of the concept by completing an equation about neutralization.

> Right, I think it is the K and the Cl potassium and chlorine forming together..[4]..potassium chloride and H_2O..[8]..and..[6]..um I guess the hydrogen chloride is breaking it down, making it less basic, I guess. Neutralizing it, I think.

Because "salt" was not mentioned it is appropriate to assume that Ishmael understood neutralization only in terms of its reactants. When I asked him if he knew what type of product the KCl (the salt) was, he replied: "No, I don't know."

Indicators and pH. Item 6 (indicators) and item 16 (pH) were incorrect while items 11, 12, and 13 were correctly answered. When questioned, Ishmael recalled the litmus (indicator) test for acids.

> *Do you know anything about acids and litmus paper?*
>
> It changes litmus paper. I don't know if it is red or blue
>
> *You don't know you never did the experiment?*
>
> We did, but I just forget because we did it with the bases.
>
> *Think.*
>
> I think it turns red.

Later, I asked Ishmael to tell me what he understood about pH?

> Um it's the level of acidity.
>
> *Just acidity?*
>
> I think so, that's all I know about it.

I asked him about pH during the follow-up interview.

> It's a measure of acidity or something, the lower the pH, the more acidic it is, and the higher the pH is, the more basic..[2]..hold it! The more basic it is. Not just a matter of acidity.

It appears that Ishmael was now able to link pH to bases as well as to acids.

If Ishmael understood pH of acids and bases he should have been able to transfer this knowledge to their ions (H^+ and OH^-). He was asked:

> *Can you say how H^+ and OH^- are related to pH?*
>
> Yeah, the OH^- if it's got more protons and less electrons the pH is lower than..[3]..the H^+; it will go anywhere hopefully the OH^- and the other way around for the H^+.

Ishmael appears confused; his explanation revolves around protons and electrons rather than the relation between the ions (H^+ and OH^-) and pH. It seems that he only associates ions with ionic bond formation and this may be the source of his problems.

Strength and Concentration. Ishmael's concept of concentration was tested by Item 24, which he answered correctly. In the first interview he was asked about the strength of acids. He was able to distinguish between a strong acid (hydrochloric acid) and a weak acid (acetic acid).

Ions. The 5 items (7, 10, 14, 16, and 21) about ions were incorrectly answered. Questioning revealed that Ishmael knew what an ion was, but that he did not link the ion concept to the other concepts on his map. These missing linkages may account for some of his misconceptions.

> *Where do they come from? What's the purpose of them, where do you find them? Things like that.*
>
> You find them in acids.
>
> *Only acids?*
>
> No, I guess you find them in, I dunno. I know you find them in acids.
>
> *How are hydrogen ions formed? Any idea?*
>
> By an electron leaving the hydrogen joining up with another molecule and it has a plus charge.
>
> *Have you ever seen this before, H^+? What is a hydrogen ion?*
>
> It's a hydrogen that's joined up with another substance.

Understanding of Acids and Bases

When Ishmael was asked to explain what an acid was, he said among other things that acids were bitter.

> An acid contains hydrogen ions and it has a bitter taste, if you get it on your skin it will sting and it is very corrosive and it is clear and colorless.
>
> *All acids.*
>
> Well maybe not.
>
> *But the ones you know actually are colorless?*
>
> Yes.
>
> *What type of substance always contain H^+?*

Hydrochloric acids.

The view that acids are bitter is not acceptable because Chemistry textbooks describe acids as sour and bases as bitter. All of the other ideas were relevant, but the only scientific concept was that of hydrogen ions. Ishmael's tendency to use everyday explanations for acids and bases is reflected on his concept map. It is significant that he mentioned hydrochloric acid as the type of substance that always contains H^+.

His word association for acids, given during the follow-up interview, was an improvement on his explanation: "strong smell," "liquid," "neutralize," "base," and "H^+ ion." He retained "hydrogen ions," and has added "neutralize" and "base."

Ishmael was able to name bases, but he did not recall the colors given by indicators in the presence of acids and bases.

Can you name some bases for me?

Name some?

Yes names of any bases.

Potassium.

Potassium what?

Potassium hydroxide and other hydroxides.

For his word association for bases he verbalized two scientific concepts, "pH" and "the hydroxide ion." The only everyday concept was "slippery."

A feature of Ishmael's interview protocol was the improvement of his concepts. I asked him about the incorrect answer he had given for Item 21.

[reading] Strongly basic--I would say "D" now.

You would say "D" now, why?

Because basic solutions contain hydroxide ions.

Here is another example: I wanted to know if Ishmael would appreciate the connection between a metallic oxide and a base, if I let him write an equation.

It might be easier if you think of an example of something which is a metallic oxide and something which is a non-metallic oxide, and try and write an equation with water.

Like that one we were doing before sort of um..[5]..KCl

No.

I don't know, I could just guess, but..

Could you write down a metallic oxide for me.

Um, (it is) MgO.

And what happens when you add water to it.

[He writes the equation correctly.] $MgO + H_2O \rightarrow Mg(OH)_2$

Oh, um would it form a base because of the hydrogen and the oxygen.

The second example not only shows Ishmael's improvement of a concept, but how chemical equations can be helpful to students who write them to describe chemical reactions.

Misconceptions

Some of Ishmael's misconceptions are listed below with relevant evidence from his interview protocol.

1. A gas is produced during the neutralization of hydrochloric acid by potassium hydroxide.

    So A is HCl, B is KOH, can you complete the equation?

    Um let me see; it goes to water. H_2O and KCl? Is this a gas?

    You have time you don't have to rush.

    Maybe they are separate, potassium and chlorine plus H_20.

2. Hydrogen is displaced from an acid after mixing with magnesium.

    The gas hydrogen where did it come from?

    From the hydrogen, oxygen (pause) mixing in the acid and the magnesium.

3. More hydrogen bonds are present in a strong acid than in a weak acid.

    Why was more gas produced with the hydrochloric acid than with the acetic acid?

[five second pause] Um, because there are more hydrogen bonds to be be broken?

Any other reason?

I don't know I am not too sure of it though.

4. Acids taste bitter and peppery.

I think the acidity has the peppery taste, the bitter taste.

5. Acids contain OH^-.

What type of substance contains OH^-?

OK, acids.

6. Substances with sharp or strong smells are acids.

Can you explain to me why you classified ammonia as an acidic substance?

I guess because it has got that sharp smell to it. Like I kind of think of it as being, I don't know, powerful. It's got a strong smell to it. That's why I guess I put it under acids.

Conclusions about Ishmael

Ishmael's score placed him at the medium level of achievement. His interview protocol and concept map reflect that he did not grasp the acid-base concepts fully and he held more misconceptions than Atlas. It was significant that during the first and follow-up interviews he corrected some of the incorrect responses he had made on the multiple-choice test, and modified what had previously been seen as misconceptions. He exhibited a sound "knowledge" of the everyday phenomena concepts and most of the base concepts. His difficulties with ions and ionic equations appeared to prevent him from making the correct links among ions, pH and related concepts.

The Case of Letty

Letty's score (9 out of a possible 25) on the multiple-choice test placed her in the low level of achievement. After some initial hesitancy, she talked freely about acids and bases giving candid reasons for her knowledge. Letty's concept map is shown in Figure 4.

Everyday Phenomena

Letty correctly answered 2 of the 5 items on everyday phenomena. Most students performed well on this subscale and it was surprising that Letty did not fare well. When Letty was given a list of substances and asked to classify them as either acidic or basic, she classified all the food materials (including fruits) as basic. It is well documented that fruits are acidic substances (Whitman et al., 1988). When Letty was asked to select an acidic and basic substance from the list of substances and to describe them both she incorrectly chose milk as a basic substance, and bleach as an acidic substance.

Letty did not seem to know about antacids because she answered Item 15 (about antacids) incorrectly. She chose *A* as her answer indicating she thought an antacid is a substance that does not react with acids. She did not know what Milk of Magnesia was. As I probed deeper it became clear that she did know the names of some antacids, but was unaware of their classification.

But the fact that they use the word acid what does it suggest to you?

It might burn his insides.

And what type of medicine, have you ever heard of the medicine being prescribed for somebody having acid stomach or burning inside?

[long pause] That's not something like Peptobismol is it?

Are you telling me?

Yes.

Sure Peptobismol.

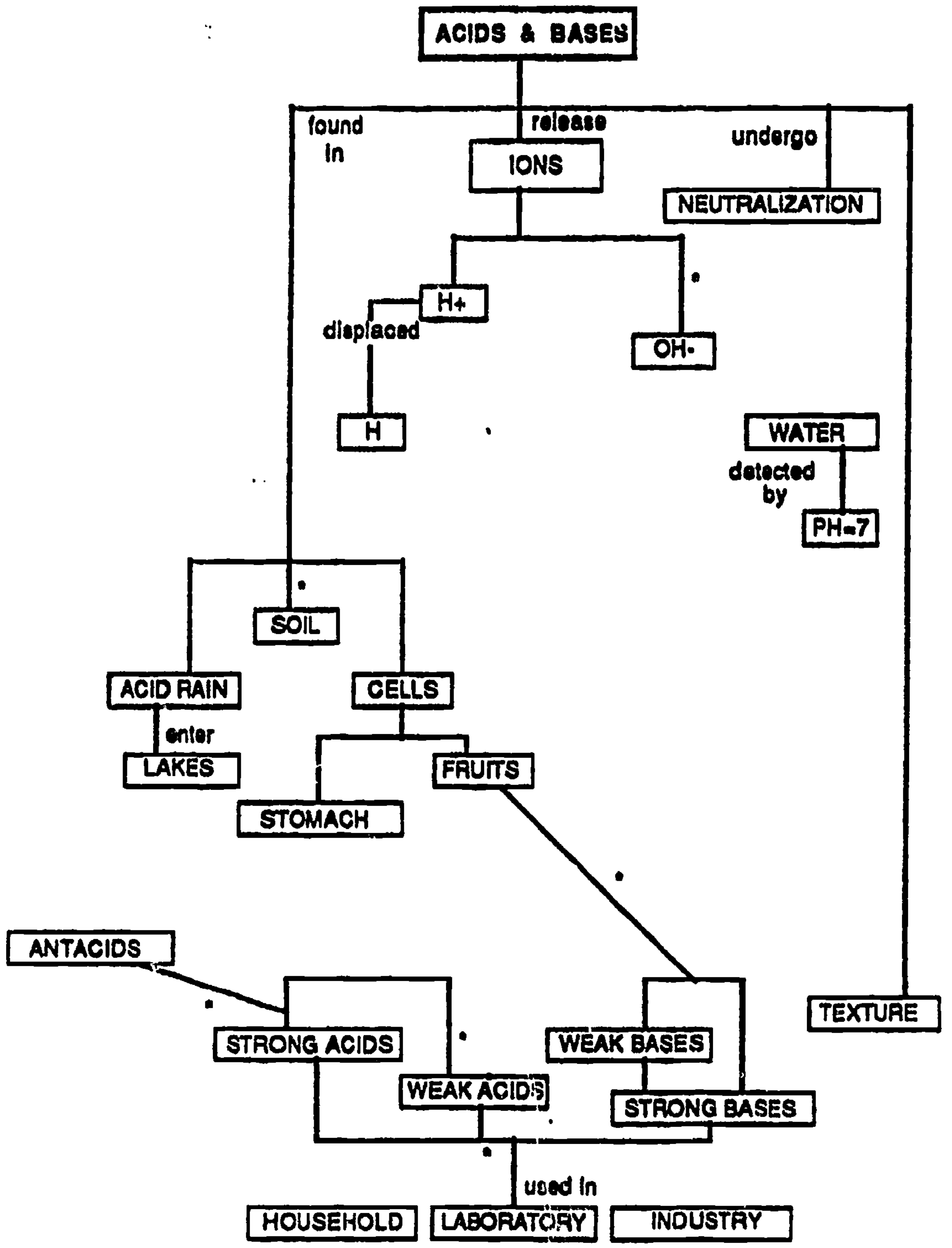

Figure 4. Letty's Concept Map

When she was asked to select gases that are produced as a result of the burning of fossil fuels, she chose carbon dioxide and oxygen.

> *OK, can you name or write the formulae for two gases produced when fossil fuels burn? Can you write formulae for the ones which are produced.*
>
> Carbon dioxide..[25]..um um.
>
> *Oh, any other gases that you can think about?*
>
> Um..[5]..oxygen gas.
>
> *OK.*

It is difficult to make conclusions from these answers but it seems she has little or no background knowledge of acid rain. When she was shown the photograph that depicted fossil fuels burning in the initial stages of acid rain formation, and was asked to explain how acid rain was formed, she said:

> But I, like it pumps up the steam and all the pollutions going up into the air.
>
> *OK and what does rain have to do with acid? Why do they call it acid rain? Are you familiar with why they call it acid rain?*
>
> Because although the pollution is in the air and when it rains it forms the acid and the rest.

Cleary Letty does not think of acid rain in chemistry terms.

Acid-Base Concepts

The concepts discussed in this section are (a) the prior concepts which are expected to facilitate Letty's understanding of acid-base concepts, and (b) the concepts found on the model concept map.

Formulae And Equations. Letty correctly identified substances "A" and "B" when given the formulae, and pH. Below, she is questioned about the information she drew from to identify the substances.

> *What do you use, the formula or the pH, to tell you that it is an acid?*

The formula.

And can you tell me what is the name of it from the formula?

Chloric acid, hydrochloric acid.

OK can you say what is the name of the B. Looking at the formula what name would you say B is?

Potassium hydroxide

Letty recognized formulae of acids and bases.

Although Letty's responses to Items 5, 7 and 18 about equation writing were all incorrect, she was able to complete the equation that was given during the interviews.

OK, I have some chemistry on A and B and I am using two formulae and I am trying to write an equation. Can you complete the equation for me?

Water plus.

Can you write it for me?

Oh the other way around [writes ClK then changes it to KCl].

$$KOH + HCl \rightarrow H_2O + KCl$$

Because Letty had incorrectly answered the items on equations it was possible she completed the neutralization equation (above) without fully understanding what had transpired during the reaction.

Chemical Reactions and the Activity Series. Letty identified magnesium as a metal but, like the other participants, she did not appear to have any knowledge of the activity series. Items 8, 20 and 25 required a knowledge of the reactions between metals and dilute acids. She answered Items 20 and 25 correctly. The correct responses suggested she knew which metals displaced hydrogen from dilute acids, but her interview protocol showed her knowledge was limited.

Can you name other metals that would have similar reactions like magnesium with acids?

Um..[12].

Do you know any other metals?

I can't think of any that would have the same reaction.

Neutralization. Although she completed the neutralization equation and identified water as one of the products, Letty seemed to think of neutralization only in terms of the reactants.

And can you explain what is happening. Now that you are looking at the equation? Do you want to try and explain anything about C?

They have been added together. And together it forms water and something else.

Two items on neutralization (14 and 22) were answered correctly, but incorrect answers were given for Items 5 and 24. But, Items 5 and 24 tested other concepts besides neutralization. Item 5 requires a knowledge of formulae, skill in balancing equations, as well as an understanding of neutralization. Item 24 is based on neutralization and the concentration of solutions. So by providing correct answers to Items 14 and 22 Letty showed that she had grasped some aspects of the concept of neutralization.

Strength and Concentration.: Letty's answer to Item 24 was incorrect, indicating a lack of knowledge of the concept of concentration. During the first interview, she recognized hydrochloric acid as a strong acid but would not concede that acetic acid was weak, only that it was not as strong as hydrochloric acid.

Would you say acetic acid is a strong or a weak acid? Acetic acid was the one which had the slow reaction.

I would still say it was strong but not as strong as the other one. So more likely..[8]..it was weaker than the other one, but I can't say it was weak.

This feature of Letty's knowledge is understandable in light of her concept of acids being strong.

pH and Indicators.: The items on pH and indicators were 6, 11, 13, 12, 16, and 23. Letty gave a correct response to Item 11, but incorrectly answered the other pH and indicator items. During the first interview Letty disclaimed any knowledge of pH.

You are not familiar with pH.

No, not at all.

Letty's answer to Item 16 was *A*. By choosing this incorrect answer (a substance with a pH of 10 is an acid) Letty showed her incomplete knowledge of the pH concept. This may also explain her wrong classification of the food substances (above). Two more efforts were made to find out what she knew about pH. The first was during an attempt to elicit "salt" as a product of neutralization.

So we have a reaction and the temperature rose. Is there anything significant about the pH of C. Look at the pH of C.

It's higher than A but lower than B, it's in between them.

Does that say anything to you.

Not really, I don't remember anything about pH.

A second attempt to elicit Letty's views about pH was made during the follow-up interview.

I asked you to name a substance with a pH of 7 and you declined?

Still don't know.

Item 11 (the only correct response) concerns a change of indicator color in the presence of acid. However, close scrutiny of the item reveals it is possible for a student to give a correct answer without knowing about the indicator, because it is common knowledge that the stomach contains acid. Letty's answers to questions about indicators were not very informative.

Suppose they ask you how would you know that a substance is an acid. How would you find out? What would you do?

Do some tests.

What (tests) would you do?

Litmus paper?

What would you do with litmus paper?

It changes color.

Can you say which colors..[4]..or you don't remember?

I don't remember.

Ions. Two items on ions were answered correctly, Items 14 and 17. Her interview protocol revealed Letty knew of the nature of ions, and that H^+ represented the hydrogen ion.

What about H^+? Hydrogen ions? Have you heard of hydrogen ions?

A little bit, it's hard to remember. Um it's a positive ion.

It's a positive ion?

Yes.

Can you say

[continues] There is only one.

What type of substances contain H^+?

Water.

Any other types?

Acids.

Anything else?

No.

Letty knew that hydrogen ions are found in acids, but further questioning revealed that she did not know that the hydroxide ion was found in bases.

What type of substances contain OH^-?

Acids.

Clearly, Letty knows more about acids than bases.

Understanding of Acids and Bases

Letty seemed to understand more about acids than bases. But, as shown [illegible] her understanding was clouded with some serious misconceptions. Of the six items on acids, Letty answered two correctly, Items 10 and 11. When I asked Letty to explain her conception of an acid, no scientific concepts were included in her answer.

Ask what else? [laugh] No, I would say that an acid is strong. It burns, it's like a chemical um ..4..it can be a liquid or a gas and it ..10.

When I asked her to give words or phrases she associated with acids, she wrote: "harmful," "powerful," "strong," "liquid," and "poisonous."

An interesting dialogue ensued when I asked Letty to give her views of bases

What about the base? What would you explain to them that a base is?

Um, I find bases harder to explain. I can't explain it as well but..[3].

Why do you think you can't explain bases as well?

Pardon?

Why do you think you can't explain bases as well?

Because acids stick out more in your mind.

Can you name some bases.

Um..[20]..[laugh]

Although I asked her for five words or phrases that represented her concepts about bases she only gave two words: "liquids," and "solutions."

Misconceptions

1. All acids are strong and powerful. Letty explains why she classified bleach as an acid.

   Bleach, it's appearance, clear, smells like really strong, like can't touch anything else, it will burn the skin and, can't drink it, can't taste it because of the burning.

   How do you use it?

   It's used in the wash to whiten clothes.

   Because it removes the stains out and because it's so strong and powerful.

2. Acidic substances are not to be ingested. When Letty classified substances as bases all the food materials were included. *Baking soda, milk, apples, tomatoes, coffee, tea, and lemon juice*. Of these, only baking soda was basic.

3. Acids are bad for your senses. Letty gave the following reason for her classification of ammonia as an acid.

> *OK, you also classified household ammonia as acidic. Can you explain why?*
>
> Um because it will burn it is really bad for the senses.
>
> *When you say for the senses; can you say, specifically what sense?*
>
> The nose, the eye, if it goes into your eye it will blind you and burn the skin.

4. Acids contain hydroxide ions.

> *What type of substances contain OH^-?*
>
> Acids.

5. Acids are poisonous.

> I can just further that by saying acids do stick out in your mind because they are so much powerful. Everyone knows the acids are poisonous. They think of ammonia and bleach and things like that. Bases, to me, I don't picture any thing in mind it just comes clear you know.

Conclusions about Letty

Letty's interview protocol and her score on the test reflect her lack of "knowledge" of everyday phenomena. This was reflected by her inability to classify substances used in the household as acidic or basic, and her incorrect answers on everyday phenomena items. Despite Letty's inadequate knowledge of everyday phenomena, she provided correct answers for two items on ions, the most difficult subscale. Her poor performance on the pH items was duplicated during the interviews. As a result her concept map is extremely sparse, when compared with the model concept map.

Summary of the Cases

Case studies have been presented for participants in the three achievement levels (high, medium and low) of the multiple-choice test. By drawing from these three achievement levels, an overview of all the students' understanding of acids and bases is obtained.

Atlas, in the top level, provided the most detailed information on the acid-base concepts, and introduced fewest misconceptions (see Figure 2). Ishmael from the medium level, despite a mediocre performance on the multiple-choice test, was able to correct some of his incorrect responses when he was interviewed for the first time. Then, in the follow-up interview Ishmael gave more appropriate responses than he had given during the first interview. Finally, Letty did not provide many correct answers on the test, nor many appropriate responses during the interviews. Of the three, Letty held the most misconceptions.

Two concepts seemed significant in discriminating between the three levels of the students' performance: pH and ions. Atlas seemed to grasp the concept of pH and all aspects of the ion concept, but could not write ionic equations. Ishmael grasped most aspects of the pH concept, seemed to know about ions, but was unable to make linkages between the ion concept and other concepts on his concept map and could not write ionic equations. Letty knew little about the pH concepts, but correctly answered more items about ions than Ishmael. Although she knew what an ion was, she thought that OH^- were found in acids.

The three participants' understanding of acids and bases was influenced by their understanding of everyday acid-base phenomena. The everyday concepts are mainly found on the left hand side of the model concept map. Atlas (at the top level) showed the best understanding of the everyday aspects of acids and bases by (a) correctly answering all items on everyday phenomena, (b) correctly classifying most of the given substances as either acidic or basic, and (c) having fewest misconceptions. Similarly, Atlas' understood more scientific concepts than the other participants. Ishmael did not understand the everyday concepts as well as Atlas, while Letty (at the low level) showed an understanding of even fewer everyday and scientific concepts.

The concept maps of Atlas and Ishmael reflect a combination of everyday and scientific concepts. However, Ishmael made fewer linkages between the scientific concepts than Atlas. On the other hand, Letty's map shows a predominance of everyday concepts for which she held many misconceptions.

More Concept Maps

Concept maps are presented for the remaining participants according to their total scores on the multiple-choice test: Crista and Mabel from the top level, Delvin and Magnus from the medium level, and Curly from the low level. (It is noted that the achievement levels for some of the participants' levels did not correspond to their Grade 11 achievement levels. For instance, with regards to the Grade 11 achievement: Atlas and Mabel were from the top level, Crista, Magnus and Delvin were from the medium level, and Curly, Ishmael and Letty were from the low level.)

Three aspects of the five participants' concept maps (Figures 5-9) are described:

1. Their concepts of everyday phenomena. They are found on the left side of the map (except for oxides) and the bottom right side (except for indicators).
2. Their scientific concepts which are the remaining concepts, after the exclusion of the everyday concepts.
3. Their misconceptions which are shown by asterisks (*).

Description of Crista's Concept Map

Crista's concept map (see Figure 5) shows all the everyday concepts found on the model concept map. Of her scientific concepts, the salt concept and the metallic oxide concept are missing, as are the concepts of the constituent ions of water, and the concept of water having a pH of 7. She holds misconceptions of everyday phenomena which include: some fruits are basic and ammonia is acidic. Also, Crista holds various misconceptions about the scientific concepts of acids and bases.

Description of Mabel's Concept Map

Mabel possessed all the everyday concepts of acids and bases (see Figure 6). Missing were the concepts of metal oxides, salts, indicators, weak and strong bases, and the constituents ions

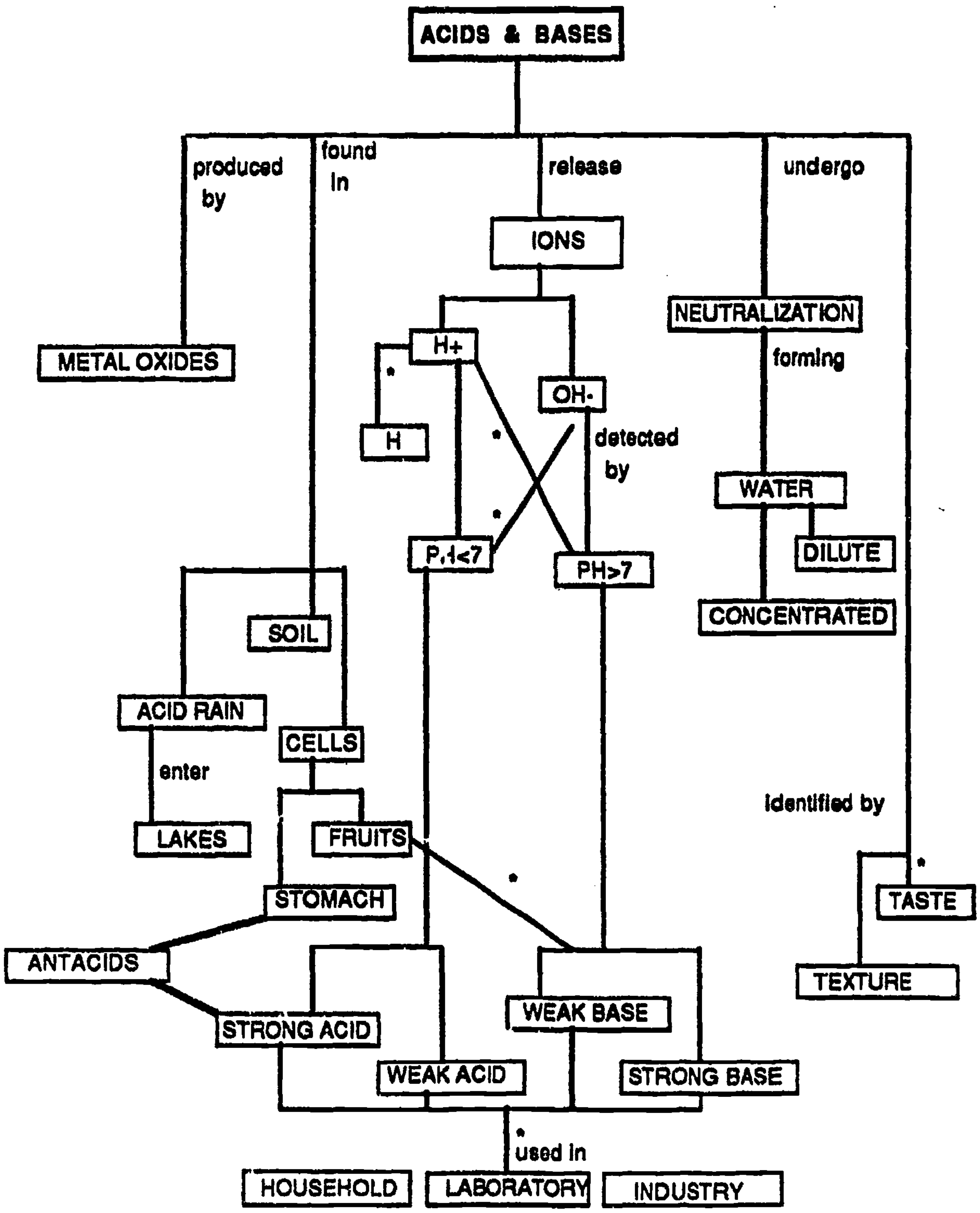

Figure 5. Crista's Concept Map

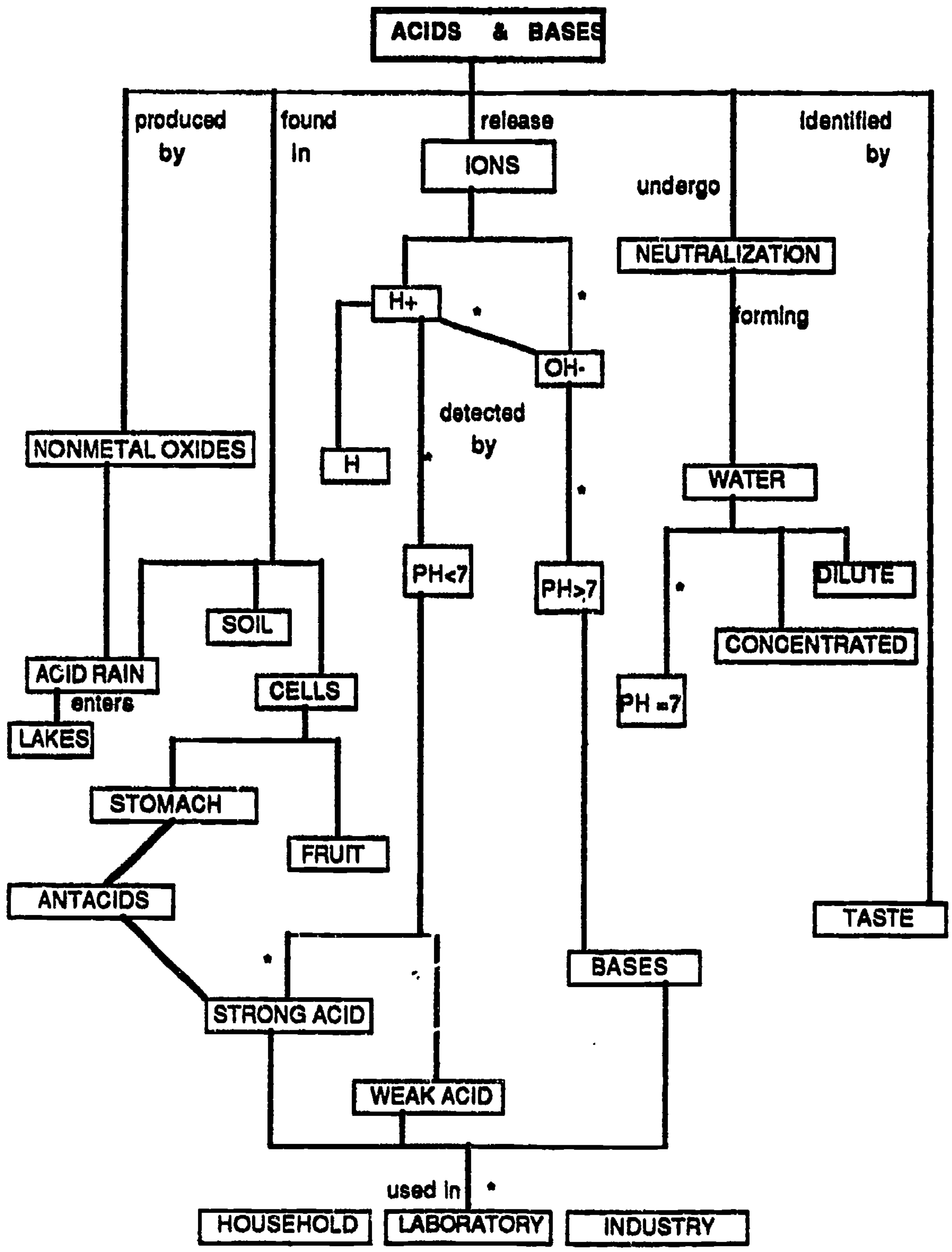

Figure 6. Mabel's Concept Map

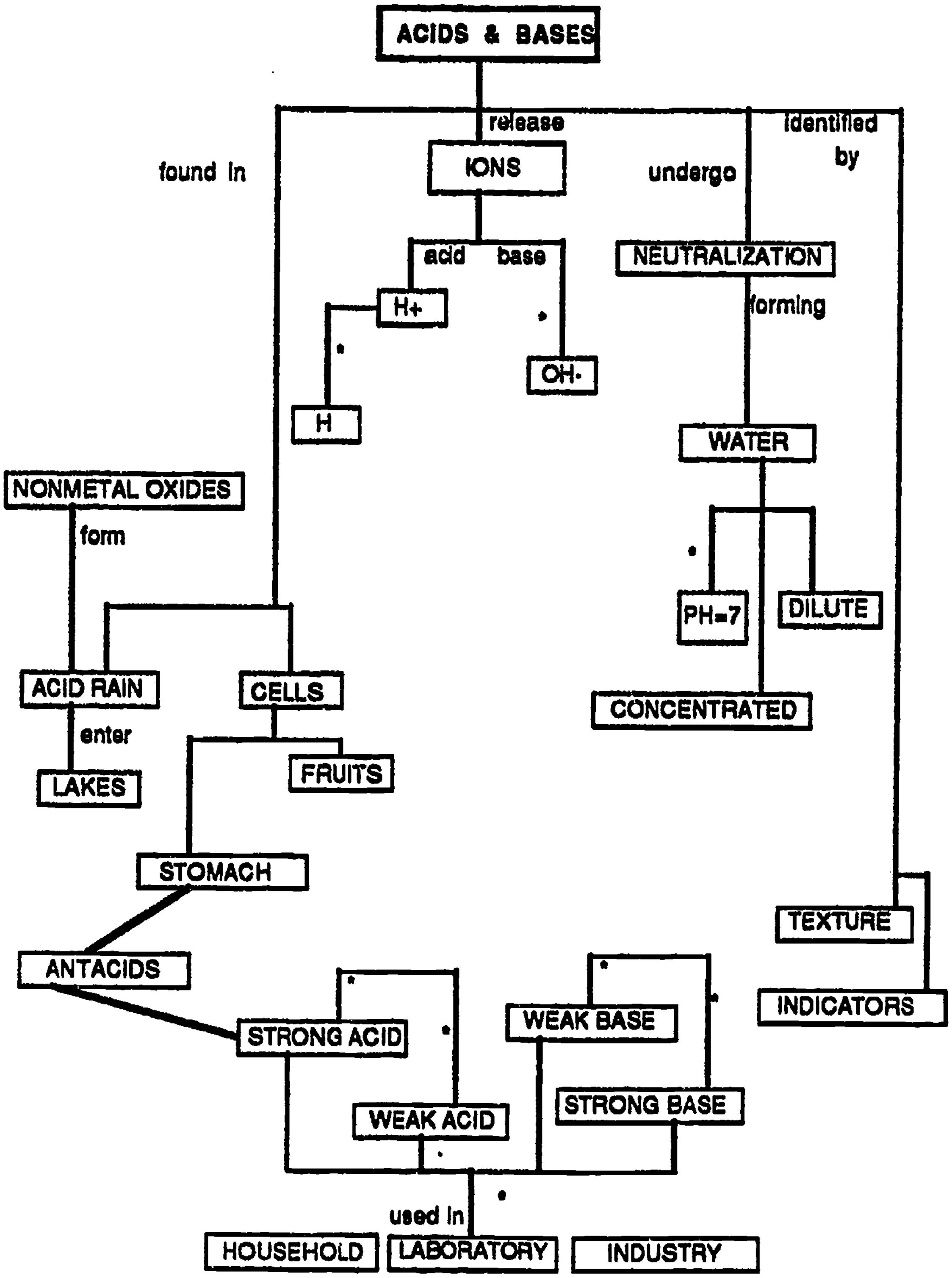

Figure 7. Delvin's Concept Map

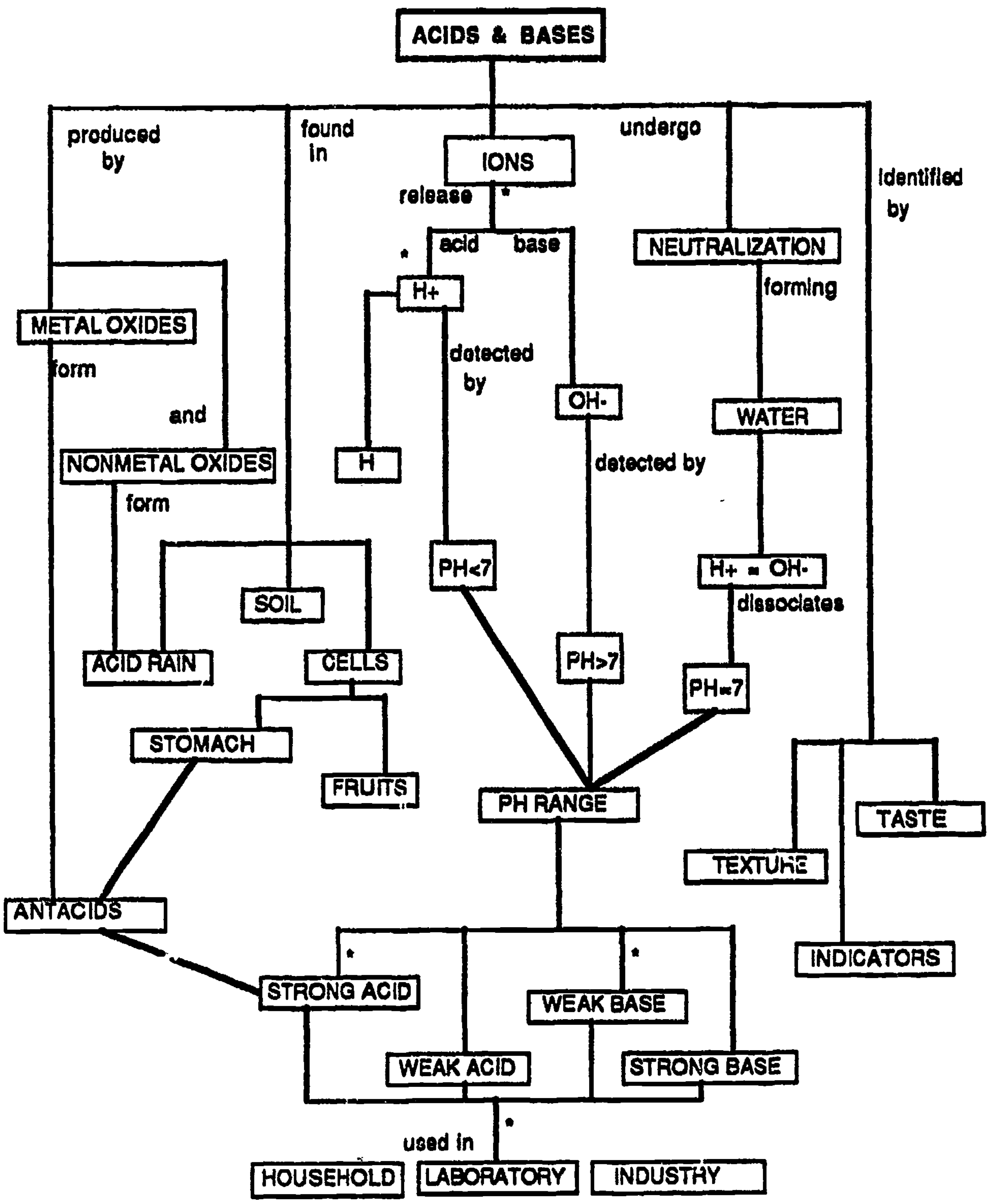

Figure 8. Magnus' Concept Map

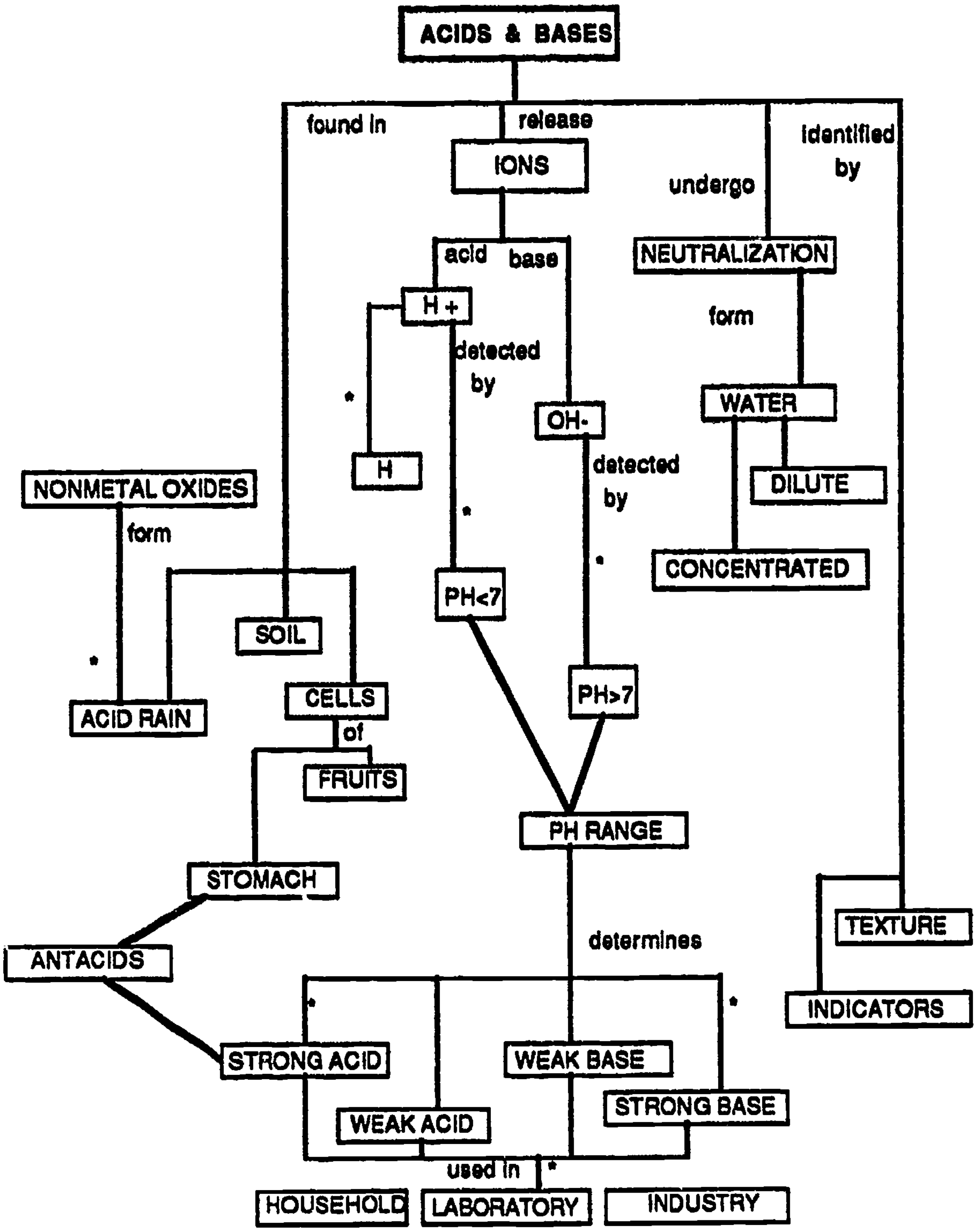

Figure 9. Curly's Concept Map

of water. Her only misconceptions on everyday phenomena were about the acidic and basic nature of some substances. Her misconceptions about the scientific concepts concerned the hydrogen and hydroxide ions and their links to pH.

Description of Delvin's Concept Map

Delvin did not classify soil as either acidic or basic which explains the omission of the soil concept from his concept map (see Figure 7). His scientific concepts did not include the following concepts: H^+ detected by a pH below 7, OH^- detected by a pH above 7, salt, metal oxides, and the constituent ions of water. Delvin's misconceptions of everyday phenomena were related to his lack of knowledge of the basic and acidic nature of household substances and soil. His misconceptions of scientific concepts were related to his inability to make links between the pH concept and other concepts. Also, he held misconceptions about the H^+ and the OH^-.

Description of Magnus' Concept Map

Magnus' references to the texture of acids and bases led to its inclusion as an additional everyday concept on his concept map (see Figure 8). Only three scientific concepts were missing: the concept of a salt, and the concepts of dilute and concentrated acids and bases. His misconceptions are about the ion concept, the concepts of acid and base strength and the acidic and basic nature of some everyday substances.

Description of Curly's Concept Map

Curly possesses all the everyday concepts found on the model concept map. His missing scientific concepts (see Figure 9) include: the constituent ions of water, the salt, the pH of water and metal oxides. His misconceptions of everyday phenomena, like those of the other participants, are concerned with the acidic and basic nature of substances. There are several misconceptions about the scientific concepts, such as the pH of acids and bases, neutralization, the strength of acids and bases and the formation of acid rain from nonmetal oxides.

Conclusions

Of the eight participants' concept maps, only two, Atlas' and Ishmael's, are not dominated by everyday concepts. The ion and pH concepts posed more problems than any of the other scientific concepts. In addition, few participants realized there was a link between oxides and acids and bases and none verbalized "salt." Despite these trends each participant's concepts were idiosyncratic. For instance, each participant grasped different aspects of the ion and pH concepts and one of the two links between oxides and bases and oxides and acids.

On the whole, the qualitative analyses support the information obtained from the quantitative analyses, and this enhances the reliability of the multiple-choice instrument. The multiple-choice items provided the subscales for the qualitative analyses and reliably separated the participants into their achievement levels. Now it is possible to use the collective quantitative and qualitative data to provide general information about the Grade 11 students.

The cases provide detailed information about the misconceptions of three participants in this study. A broader representation of the misconceptions held by the participants is provided in chapter 5. There, the quantitative and qualitative data are analyzed by themes.

Chapter 5

Thematic Analysis of Data

In the previous chapter the three case studies and eight concept maps provided information concerning the participants' understanding of acids and bases. This chapter presents a thematic analysis of the quantitative and qualitative data with the intent to describe the students' understanding of acids and bases. The selected themes identify the students' prior knowledge of relevant chemistry and science topics before instruction on acids and bases, their concepts of acids and bases after Grade 11 instruction, and their misconceptions. The themes of prior knowledge and misconceptions emerged from the data, while the theme of acid-base concepts and its sub-themes emerged after the construction of the model concept map. Although these themes and sub-themes are not exhaustive, they represent the major constituents of the students' understanding of the topic. The chapter begins with a clarification of the themes chosen and their justification. Throughout the chapter special attention is given to the participants whose cases were not presented in chapter 4, and all the students' difficulties and confusions are considered in light of their contribution to basic misconceptions.

The concept maps shown in chapter 4 revealed that each participant's knowledge and understanding were idiosyncratic although each student had received the same science and chemistry instruction. Also, the concept maps revealed that the participants' concepts are biased towards everyday concepts. It is justifiable to identify factors, in the classroom or outside the classroom, that may have contributed to each student retaining idiosyncratic concepts.

Classroom factors can be divided into two categories. In the first category are the acid-base concepts that students acquired from (a) primary school general science, (b) high school general science, and (c) chemistry classes that preceded their formal instruction on acids and bases. The concepts include symbols, metals, ionic bonding, atomic structure, molecular and ionic formulae, writing equations, metals and their oxides, nonmetals and their oxides, strong and weak electrolytes, and dilute and concentrated solutions, and are collectively termed prior knowledge concepts in this study.

In the second category of classroom factors are those concepts acquired during Grade 11 chemistry instruction on acids and bases. These concepts include pH, neutralization, ions, and other concepts on the model concept map. Ions are included in the first and second category because the the concept of ions is typically introduced in the early stages of chemistry instruction and is therefore a prior knowledge concept. Similarly, the position of the ion concept on the concept map justifies its inclusion as an acid-base concept.

The other factors will be termed everyday phenomena (as in chapters 3 and 4). Outside the classroom, students encounter everyday acid-base phenomena, such as the nature of antacids (through radio and TV commercials), acid rain (through the media's reports of environmental hazards), and battery acid (through encounters at home or at the mechanic's).

Prior knowledge and everyday knowledge acquired and integrated in the students' cognitive structures before instruction on acids and bases are not easily challenged or replaced (Osborne & Cosgrove, 1983; Mayer, 1987). Therefore it is expected that any misconceptions that accompany students' prior knowledge and everyday learning will lead to other misconceptions, when acids and bases are taught formally. In the light of the above, the major constituents' of students' concepts of acids and bases will be presented in the themes below.

1. Students' prior knowledge. This includes the general science and chemistry concepts students were expected to acquire before instruction on acids and bases, and which the participants' verbalized during the interviews.
2. Acid-base concepts. These are the concepts found on the model concept map. It must be noted, no separate sub-themes are considered for either indicators or concentrated and dilute solutions. Indicator concepts are related to pH, and provide what Whitman et al. (1983) call

operational definitions for acids and bases. No sub-theme is made for indicator concepts because of their overlap with pH and their dependence on recall. On the other hand, the concept of concentration is related to the mole concept which is beyond the scope of this study, and will be excluded.

3. Students' concepts of everyday phenomena. These include students' knowledge of acid rain, antacids, "battery" acid, acidic and basic household substances, and any other related material verbalized by students during the course of the interviews.

4. Understanding of acids and bases. Conclusions are made about the participants understanding, based on the multiple-choice instrument analyses, the linkages or lack of linkages between concepts on the students' maps, and students' summaries and word associations for acids.

5. Misconceptions. These misconceptions are strictly related to the participants' notions of what constitutes an acid and a base.

Prior Knowledge.

Prior knowledge concepts are those encountered in early science classes and in the Grade 11 advanced chemistry class, prior to instruction on acids and bases. They are not found on the model concept map, but are introduced during the interviews. Ausubel's (1968) assertion that prior knowledge is the most important single factor influencing learning has been endorsed by Novak (1981; 1984) and supported by many others including Chandran, Treagust and Tobin (1987), who showed its importance for chemistry learning.

The following sub-themes are included as prior knowledge:

1. Atomic Structure, Bonding, Symbols, and Formulae.
2. Activity Series of Metals.
3. Chemical Reactions and Equations.

Atomic Structure, Bonding, Symbols and Formulae

This sub-theme concerns the students' knowledge of the structure of atoms, elements and their symbols. Students are also expected to know that metallic and non-metallic elements form ions which bond to form ionic compounds. The formulae of these compounds may be written as ions or molecules, and indicate the number of atoms they contain.

Students who were familiar with the constituents of the atom correctly answered most questions about ions and bonding, although some experienced more difficulty than others. For example, Ishmael who was asked if there was a difference between a hydrogen ion and a hydrogen atom replied: "Oh plus, it's got more protons than electrons." Ishmael was able to recall that a typical positive ion has more protons than electrons. (The hydrogen ion has only one proton, it has no electrons.) On the other hand, Magnus (from the medium level of achievement) faltered before answering questions about hydrogen atoms.

When you see H written by itself what is it?

Magnus: Hydrogen.

Hydrogen what?

Magnus: Hydrogen gas?

OK, what amount of hydrogen gas does it represent?

Magnus: Two electrons.

I had expected Magnus to say H represented one atom of hydrogen, and was surprised at his answer. So, I continued the discussion during the follow-up interview.

When I spoke to you last time I showed you the symbol H, for hydrogen, and the symbol H^+ for hydrogen ion, you commented about hydrogen (atom), you said that this represented two electrons. I am not sure if that is what you wanted to say. Do you recall that.

Magnus: Uh..[7]..that's not right.

Although Magnus did not offer the correct answer, he recognized that he had made an error.

All of the participants recognized chemical symbols, so it can be assumed that the difficulties students experienced (Items 2 and 3) in identifying solutions formed from metallic and non-metallic oxides were not caused by a lack of knowledge on symbols. However, some participants experienced difficulty when they were asked to identify chemical formulae. In the dialogue below, Mabel, who was in the top level of Grade 11 chemistry achievement, is asked to identify KOH.

Mabel: It does not have a hydrogen. I guess it is potassium hydride. It's not an acid.

What's the name of it?

Mabel: Potassium hydride.

Potassium hydride? Did you ever hear of potassium hydroxide?

Mabel: I am not sure.

Students who do not recognize formulae will not be able to extract information about the rearrangement of atoms into new substances, from equations. This may explain why the test items that required students to extract information from equations, gave problems.

Activity Series of Metals

The activity series of metals is a list of metals placed in order of their reactivity. The metals above hydrogen in the activity series, displace hydrogen from water and dilute acids. The inclusion of the activity series as a prior knowledge concept is justified because of its inclusion in the curriculum. According to the Chemistry Curriculum Guideline: "The student is expected to: observe and compare the activity of metals and develop an activity series for them" (p. 14). All of the students identified Mg as the symbol for magnesium and classified magnesium as a metal. Items 8, 20, and 25 concerned reactions between acids and metals. Students answered these items reasonably well (14, 20 and 20 correct answers respectively). However, none of the participants seemed familiar with the activity series of metals but some used their knowledge of the periodic table to answer questions about metals reacting with dilute hydrochloric acid. Only one participant (Atlas) was able to name four metals that react with hydrochloric acid in a way similar to magnesium.

Curly (in the low level of achievement) gave this answer when he was asked to classify magnesium and to name other metals with similar reactions.

Curly: It's a metal.

It's a metal. Can you name other metals that have similar reactions with X and Y.

Curly: Um..[9]..I think zinc.

Anything else?

Curly: We did something along that line, I know what it is, but I can't remember offhand.

A knowledge of the activity series would enable students like Curly to predict which metals react with dilute acids. However, if this knowledge is lacking, students tend to form misconceptions about acids. For example, Crista thought copper reacted with dilute acids. This is incorrect because copper reacts with concentrated acids only. If Crista had knowledge about the activity series she might not have verbalized copper. (Gold, silver, mercury and copper are the metals in the series which do not react with dilute acids.)

The students' incomplete knowledge of metals and their reactions may be the reason that they lack knowledge about salts and bases. None of the participants seemed aware that a salt is one of the products of neutralization. Also, base items ranked as the second most difficult subscale on the multiple-choice test.

Chemical Reactions and Equations

During the first set of interviews, the participants were presented with cards that related information about potassium hydroxide and hydrochloric acid (KOH and HCl). They were shown the pH values and temperatures of the two substances before they were mixed, and the temperature of the resultant mixture. One purpose of the exercise was to determine whether the participants associated the production of heat during the neutralization reaction with a chemical change. Results of an earlier study, (Cros et al., 1986) indicated that first-year university students did not associate heat release with neutralization. Although the participants in the present study identified heat release as a sign of a chemical reaction, other notions were revealed. Below, Curly is asked about the reaction of potassium hydroxide and hydrochloric acid.

> *Now we are going to add A and B (potassium hydroxide and hydrochloric acid) to get substance C. Can you say what type of substance C represents?*
>
> Curly: C represents, would it be a solution between A and B?

Earlier, Curly had correctly associated the release of heat as a sign of a chemical change. The above response shows that he has a misconception about chemical change, confusing it with physical change. The formation of a solution is a physical change. Substance C was not a solution of A and B but a new compound. Curly's misconception was shared by Delvin (from the medium level of achievement), who stated that the base dissolves in the acid neutralizing it.

> Delvin: That tells you that there has been a reaction and that I think the base is dissolved in the acid, neutralizing it.

Later, asked why the reaction between magnesium and X (acetic acid) proceeded more slowly than that of magnesium and Y (hydrochloric acid), Delvin responded: "Oh because the magnesium was absorbed a lot quicker."

He thought the acid had absorbed the magnesium, but later changed his statement to "dissolve."

> Delvin: Y?
>
> *You see in the case of X that didn't happen. Is there something special about Y what do you think?*
>
> Delvin: I guess it just took longer for it to dissolve.

In these examples, Curly and Delvin use their own reasoning to explain what occurs during a chemical reaction (Driver at al., 1985; Linn, 1987). Students are expected to explain that a chemical reaction is accompanied by bond making and bond breaking. And, if they write equations whenever they described chemical reactions they might. But understanding equations has already been identified as a problem from analyzing the quantitative data. Six of the participants in the present study who completed the neutralization equation during the interviews, were unable to transfer information to novel situations. The two participants who transferred information to novel situations (Ishmael and Mabel) were able to predict the products of chemical reactions, by writing the formulae of two reacting substances and completing the equation.

The data reflect varying abilities in writing equations. For example, Ishmael completed the molecular equation,

$$KOH + HCl \rightarrow KCl + H_2O$$

but could not complete the corresponding ionic equation.

$$K^+.OH^- + H^+.Cl^- \rightarrow$$

As he attempted the task, he said:

> Right, I think it is the K and the Cl potassium and chlorine forming together..[4]..potassium chloride and H2O..[8]..and..[6]..ahm I guess the hydrogen chloride is breaking it down, making it less basic, I guess. Neutralizing it, I think.
>
> *Now, I have some ionic equations instead of molecular equations. Can you complete the ionic equation?*
>
> Ishmael: Ah Jesus, is it water?
>
> *Is it something you have forgotten .*
>
> Ishmael: Oh I just can't remember..[10]..um

In contrast, Delvin was unable to complete any type of equation.

> *A is HCl, B is KOH. You may write here if you choose to.*
>
> Delvin: [starts to write then stops]..15..I can't remember how to do it.
>
> *This is a different type of equation, an ionic equation, but it represents the same reaction.*
>
> Delvin: Yes.
>
> *Can you complete the equation.*
>
> Delvin: [pause of thirty seconds] No.

Interestingly, as shown in Table 7, the students who were skilled in equation writing tended to understand acid rain formation, and neutralization, more readily than the less skilled. Table 7 is a summary of the nature of the participants' answers to questions about concepts, typically introduced before instruction on acids and bases. (In Tables 7-10 the total number of participants with correct and incorrect responses is eight.)

Table 7.

Participants' Answers to Questions on Selected Concepts

Concepts	No. correct	No. incorrect
Symbols & Formulae	8	0
Ionic Bonding	3	5
Metals	7	1
Activity Series	0	8
Molecular Equations	6	2
Ionic Equations	3	5
Indicators	4	4

It is clear from the information presented in Table 7 that the students' knowledge of some prior concepts, such as ionic bonding, the act[illegible]ries, and ionic equations was inadequate. In light of what Driver et al. (1985) found, "ch[illegible]n have a tendency to interpret new situations in terms of what they already know thus reinforcing their prior conceptions" (p. 198), it can be predicted that students' knowledge of the acid-base concepts, discussed below, will likewise be inadequate.

Acid-Base Concepts

Five sub-themes are included as acid-base concepts: strength of acids and bases, metallic and non-metallic oxides, pH, neutralization, and ions. These concepts are found on the model concept map.

Strength of Acids and Bases

No item concerning acid and base strength was written, but the participants' concepts were elicited during the clinical interviews. The concept of acid and base strength, shown on the concept map, is linked to pH and most of the participants saw it in this light. Strong acids and strong bases almost completely dissociate into their constituent ions in solution. Weak acids and weak bases only partially dissociate.

Each participant was shown cards relating the reaction of magnesium and dilute hydrochloric acid, and magnesium and acetic acid. Magnus showed his understanding of the concept of acid strength when he was asked about the nature of acetic acid. In his answer he linked the strength of acetic acid to its pH.

Would you say it is a strong or weak acid?

Magnus: Weak.

Weak acid why?

Magnus: It does not have a high pH, I mean low pH, and because it does not react as fast.

Magnus, correctly, indicated that acetic acid is a weak acid. His explanation refers to the pH rather than to the amount of ions released by hydrochloric acid compared to acetic acid. This explanation is acceptable, and it is an example of what Cros et al. (1988) referred to as a descriptive definition. What would have been more appropriate is the scientific definition. But, in order to give a scientific definition participants are required to verbalize about the strength of acids and bases in terms of ions, and it was already shown that the participants had difficulty with items on ions. As shown in chapter 4, Letty and Atlas held misconceptions about the strength of acids. And, Delvin argued that acetic acid is a strong acid because magnesium took a longer time to break down acetic acid than it took to break down hydrochloric acid. Table 8 is a summary of the participants' responses to questions about the strength of acids and bases.

Table 8.

Participants Responses to Questions on Strength and Concentration

Proposition	No. correct	No. incorrect
Strong Acids	7	1
Weak Acids	6	2
Strength and pH	2	6
Strength and Ionization	5	3
Strength and Concentration	2	6

The majority of the participants know about the strength and concentration of acids and bases, but do not make the links between them and other concepts.

Oxides

The left side of the concept map shows the link between metal oxides and bases and the link between nonmetallic oxides and acids. Most students seemed unaware of these links. As a stimulus during the clinical interviews, participants were shown pictures of smoke coming from stacks where fossils fuels burned. After hinting that the gases in the smoke eventually formed acid rain, the author asked the participants to identify the gases that caused acid rain formation. Their answers included carbon dioxide, oxygen, and carbon; and the three participants who gave accurate answers required more than one attempt. Some students did not even verbalize "oxide." Two participants, Ishmael and Delvin, named "carbon" as the gas; Curly said "chlorine," and Mabel said "oxygen." Crista declined to answer, and Magnus and Atlas said "carbon monoxide." If the participants were aware of the link between non-metallic oxides and acids they might all have named an oxide. Responses to the multiple-choice test show a similar pattern. Only 16 students answered Item 18 correctly. Item 18 required students to identify the gaseous oxide which reacted with water to form an acid found in acid rain. There is evidence that if students know non-metallic oxides form acids with water, and possess skills in equation writing, they can understand the scientific explanation for acid rain formation. For instance, Mabel who knows how to write chemical equations discovers one of the acids found in acid rain.

All right, do you care to write the equation for the reaction between the gas you identified and the rain to give the acid.

Mabel: [shakes her head and writes the equation]

$$H_2O + SO_2 \rightarrow H_2SO_3$$

So what is the name of the acid?

Mabel: If it were a four, it would be sulfuric acid.

OK

Mabel: I think it should be [laughs pointing to H_2SO_4].

I could probably tell you about this later but it is interesting to me that now you write the equation you have been able to name the acid

Mabel: So I could have done it before. [laughs]

Later, the author was also able to show Ishmael that water added to a metal oxide resulted in the production of a base.

Could you write down a metallic oxide for me

Ishmael: Uh, um MgO.

And what happens when you add water to it.

[He correctly writes] $MgO + H_2O \rightarrow Mg(OH)_2$

Ishmael: Oh, um would it form a base because of the hydrogen and the oxygen.

Here Ishmael's skill at writing equations appears to improve his understanding of bases. In contrast, a similar strategy to show him the connection between nonmetallic oxides and acids was unsuccessful.

pH

The topic pH is typically introduced to students before formal chemistry instruction on acids and bases. Accordingly, students use indicators to distinguish between acidic and basic substances and to determine pH levels of substances. Acids have pH values less than 7 while bases have pH values greater than 7. Also, a substance with a pH value of 12 is more basic than a substance with a pH value of 8. A substance with a pH of 1 is more acidic than a substance with a pH value of 4. The multiple-choice test results suggested that the pH concept (which occupies a central position on the model concept map) was well understood by most students. As shown in chapter 4, the participants' interview protocols provided contradictory evidence. Students were only found to have acceptable viewpoints for pH when it was used in connection with everyday phenomena. For example, Crista was told "Rob" was diagnosed as having "acid stomach" and asked what remedy the doctor would suggest.

What type of medicine is the doctor likely to prescribe for Rob?

Crista: Something that would have a pH greater than 7 like the Milk of Magnesia.

However, probing revealed some misconceptions. Below, the participants were asked "What is pH?"

Crista: [laugh] It's the measurement of acidity in a substance that's it.

(later)

Crista: So below 7 it's basic 7--it's neutral. Above 7 it is acidic.

Ishmael: Um it's the level of acidity

Just acidity?

Ishmael: I think so that's all I know about it.

But later he produced a more acceptable viewpoint.

Ishmael: It's a measure of acidity or something the lower the pH is the more acidic it is and the higher the pH is the more basic..[2]..hold it! The more basic it is. Not just a matter of acidity.

Delvin: From what I remember it was classifying the amount of acidity in a substance.

Curly: pH is the level of which, it sounds like an acidity rating.

Acidity rating, just acidity?

Curly: Acidity and neutral rating it makes it's base level or acidity level.

Mabel: Yes, it's um, is it the hydrogen? A pair of hydrogen atoms or something like that I don't, I am not too sure.

(I returned to the topic later)

Mabel: It's with the basic or acidic level. I can't remember it's one of them.

Why? Both of them or one of them?

Mabel: It's one of them.

Atlas: Um the level of acidity in the substance.

And the pH measures; is it (pH) the measure of the level of acidity?

Atlas: That's right.

Curly: I think the pH works on the fact that the amount of OH in the acidity level H. In the substance..3..basically what basically what changes. I am not sure.

Five participants (Crista, Ishmael, Delvin, Curly and Atlas) said pH referred to the acidity level. Crista seemed confused by numbers and because she had said pH was a measure of the acidity level she added "above 7 it is acidic." It may be confusing for some students to think of a decrease in the pH number as an increase in the acidity. For example, if the pH of a substance changes from 5 to 3 it becomes a stronger acid. The six quoted views show students' preference for verbalizing pH in terms of acids; this is not acceptable. Only Ishmael verbalized base when he gave his explanations of pH. Though Ishmael mentioned the acidic and basic aspects of pH, his answer was incomplete because there was no mention of the neutral point (pH 7). Mabel was not even sure whether pH measured the acidity level, or the basicity level.

The mathematical definition for pH (Whitman et al., 1988) is given as the negative logarithm of the hydrogen ion concentration. When I asked students if they knew what the different pH values measured, they replied in the negative.

> Crista: What is being measured? [shaking head for no]
>
> Ishmael: [laughs] I don't know.

One student, Letty, disclaimed any knowledge of pH.

> Letty: Not really, I don't remember anything about pH.
>
> *You are not familiar with pH.*
>
> Letty: No, not at all.

Six participants (see Table 3) either could not name a substance which had a pH value of seven, or named substances which were unexpected. Here is an example.

> Crista: [reading the card] What has a pH of 7? That's got to be neutral. Can't think, tomatoes? [writes: tomatoes pH 7.]

I returned to the discussion with Crista during the follow-up interview.

> *OK. I asked you to name a substance with a pH of 7. You said tomatoes. Would you tell me why?*
>
> Crista: Why? [laugh] I don't know it seems basic, it does not seem like it's. It seems neutral like it doesn't seem acidic or basic. I don't know.
>
> *Is there any other substance which has a pH of 7?*
>
> Crista: 7?

Table 9 shows the links participants made between pH and other concepts.

Table 9.

Links made by Participants between pH and other Concepts

Proposition	No. correct	No. incorrect
Water and pH = 7	2	6
Acids and pH < 7	7	1
Bases and pH > 7	5	3
pH and Ions	4	4

As noted in chapter 3, the pH subscale ranked second in ease behind the everyday phenomena subscale suggesting the participants would answer question about pH easily. However, the misconceptions revealed in the analysis of the quantitative data indicated that the multiple-choice test requires additional items on pH if the test is to derive an accurate assessment of the students' ideas.

Neutralization

Quantitative analyses revealed the neutralization concept as being moderately difficult and this was substantiated by the participants' protocols. The participants seemed to grasp the concept of neutralization as it pertained to the reactants (an acid reacting with a base), but not all realized that water was one of the products of neutralization. Also, no particiant mentioned "salt" during the interviews, despite some deliberate attempts to elicit this word. Besides water, a salt is produced during neutralization. Here are two examples of the attempts to elicit "salt."

In the first example, I asked Crista about the substance C, which was formed when hydrochloric acid reacted with potassium hydroxide.

Can you say what substance C represents.

Crista: It is the pH. It is a neutralized solution.

Anything else?

Crista: It's equal to A and B.

Is there anything significant about the temperature of C?

Crista: It's greater that means there was a reaction.

Is there anything significant about the pH of C?

Crista: It tells you that um, I guess there was enough B to neutralize all of A.

Delvin was asked similar questions.

Delvin: A reaction between the acid and the base neutralizing the acid.

Oh is there any special name you would call C?

Delvin: There is, but I can't remember.

It was interesting to note the different ways students conceptualized neutralization. They seemed to prefer to use ordinary everyday language for its description. For instance, although Crista proved that she was able to give a correct scientific explanation for neutralization, she also gave this explanation "It was an equal like reaction. There were no left over parts." Yet students gave competent explanations about neutralization when they verbalized about everyday phenomena.

And when someone has that problem (acid stomach), what medicine is the doctor liable to prescribe?

Curly: Some sort of neutralizer for the acid, milk, a base, or some sort of Milk of Magnesia.

Mabel: Um it neutralizes the acids in your stomach.

No participant linked the formation of a salt to neutralization. However, six participants realized that water was one of the products of neutralization and five participants verbalized neutralization when asked about antacids. Students' problems with neutralization may be due to their lack of knowledge about salts.

Ions

Students' concepts of ions may be the most significant factor underlying their understanding of acids and bases. This is because the participants who made more linkages between the ion concept and other concepts seemed to have fewer misconceptions. Certainly, the ion sub-theme was found to be the most difficult for the participants. An understanding of the ion concept is important if students are to have a scientific knowledge about acids and bases. As shown in chapter 4, a knowledge of ions was the factor which determined whether students held an everyday type view or a scientific view of acids and bases. When some of the participants were asked about the substances which contain hydrogen ions Delvin and Mabel gave unexpected answers.

Crista: Acids.

Ishmael: Hydrochloric acids.

Delvin: Something like water.

Anything else?

Delvin: Not specifically.

Letty: Water

Any other types?

Letty: Acids

Mabel: The ah, the ones like you have hydrogen here and all the one plus (+) things here and then you have the group the seventh group. I don't know what they are called though?

Atlas: Ah, often an acid will.

Delvin and Mabel have not associated acids with hydrogen ions although they freely verbalized about acids. Later, I asked the participants about hydroxide ions and more unanticipated answers surfaced.

Crista: That's um OH^-. hydrogen..[3]..we, I don't recognize that from the equations that we did. It's not ammonia and it's not. I don't remember. I don't know.

You know it but you don't remember?.

Crista: That's right.

Ishmael: OK acids.

Letty: Acids

Atlas: Will be a base.

Mabel: Acids.

Acids?

Mabel: Hydrochloric acid, sulfuric acid.

That three participants would say the hydroxide ion is found in acids was a cause for concern (bases is the correct answer). So during the follow-up interview I asked Mabel about the answer she had given in the first interview.

I have here in my notes that you said OH^- and H^+ are found in acids. Am I correct with my transcription? When I checked here, I found that you said OH^- were found in acids and H^+ were found in acids.

Mabel: I don't remember but if it is on the tape then probably the acid.

But would you want to change that?

Mabel: Isn't one of them in bases and isn't one of them in acids? Like OH^-, I think is more in acids, isn't it?

Her answer was still incorrect. As noted earlier, Mabel was one of the students in the top level of achievement in Grade 11, so she was expected to identify H^+ as the acid ion, and OH^- as the base ion.

The following answers were given to questions about the relationship between hydrogen ions, hydroxide ions, and pH.

Ishmael: Yeah, the OH^- if it's got more protons and less electrons the pH is lower than..[4]..the H^+; it will go anywhere hopefully the OH^- and the other way around for the OH^-.

Mabel: Not too sure, I think that like this determines the acidic and basic level of the pH.

Atlas: Um the higher..[5]..the substances which contain more OH^- or generally were related to OH^- will have a higher pH number, while the greater H^+ will.

Only Atlas gave an acceptable answer to the question. Clearly, this is another example of the difficulty students found when answering questions about ions. One must assume that although the participants knew what a hydrogen ion was, they were unable to link it to other concepts. Table 10 presents an overview of the links made between ions and other concepts.

Table 10.

Links between Ions and other Concepts

Proposition	No. correct	No. incorrect
Ions and pH	4	4
Ions and Bases	5	3
Ions and Acids	7	1
Ionic equations	3	5
Ionic formulae	5	2
Acids and H^+	6	2
Bases and OH^-	4	4

The evidence provided in Table 10 shows that the participants' knowledge and understanding of ions was inadequate if they were to understand all the concepts of acids and bases. Indeed, the table reflects that they are deficient in their knowledge about bases.

Everyday Phenomena

So much has been written before about everyday phenomena that it is not necessary to discuss this theme at length. The quantitative analyses showed students were knowledgeable about this subscale. However, probing during the clinical interviews revealed participants held misconceptions about everyday phenomena. For example, one participant classified all the foodstuffs as basic substances; and only two participants knew the chemistry of acid rain. Here are some interview excerpts that reflect the participants' concepts of everyday phenomena. I asked Letty why she thought bleach was acidic.

> Letty: Because it removes the stains out and because it's so strong and powerful.

Curly was asked why he had classified ammonia as acidic.

> Curly: I did that because it works on the same principle as lemon works, it cuts your grease and stuff. Lemon works as an acid, the juice cuts the grease.
>
> *So you are saying ammonia cuts grease like lemon.*
>
> Curly: Yes.

Both bleach and ammonia are basic. Clearly, the two responses reflect misconceptions about acids. When questioned about acid rain all the participants, except Letty, gave adequate descriptions of acid rain although they did not address its scientific aspects. Letty had problems with both the descriptive and the scientific aspects.

Understanding of Acids and Bases

Evidence from the quantitative analyses and the interview data show that the students know more about acids than bases. This is consistent with what Cros et al. (1986) found in their study on first-year university students' notions of acids and bases.

During the first set of interviews, students were asked to imagine th.y were explaining the nature of acids and bases to someone they knew. Then, at the end of each follow-up interview, students were asked to mention five words or phrases, that came to their minds when they thought about an acid and a base. Below, the participants give their explanations and their word associations for an acid and a base.

Acids. When asked for words that represented their concepts for acids, the participants said acids were "harmful," "dangerous," "corrosive," "powerful" or "burned." Letty gave "strong," "powerful," and "burns" as three of her word associations for an acid. Two students each used two scientific words for acids. Ishmael used "neutralize," "H^+" and Atlas mentioned "H^+," and "pH." Magnus' explanation of an acid was: "It has a low pH, it causes a burning effect if it touches anything, it is very dangerous, it is near normal and it is dangerous."

It is not unusual for students to be warned about the dangers of concentrated acids. (This is necessary in school science laboratories.) However, after formal chemistry instruction students should distinguish between the properties of concentrated and dilute acids, and should know that certain weak acids are found in fruits and in other edibles. Most of the concepts verbalized were typical of the everyday view of (concentrated) acids.

Few of the participating students seemed inclined to think of acids in terms of their scientific concepts, for example pH and ions. Their knowledge of everyday phenomena was better than their knowledge of the prior knowledge concepts, so it is not surprising that most students preferred to use descriptive words rather than scientific words (like pH and ions) to explain acids.

Bases. As mentioned before, students performed poorly on ion and base items. Unlike ion concepts, base concepts are not seen (by the author) as difficult for students to understand. Rather, students' problems with bases may stem from their conceptions of bases being slippery, neutral, odorless, safe, slimy and liquid. Only two participants felt bases were dangerous, one participant used "OH^-" to describe bases, while six participants said bases were "slippery," and four participants mentioned that bases would neutralize acids. Crista was unable to think of any names for bases. Although Atlas gave an adequate scientific description of bases he had initially avoided the discussion by saying less is known about bases.

Misconceptions about Acids and Bases

This final section highlights some of the participants' misconceptions. Unlike other misconceptions previously identified, they are strictly related to the participants' notions of what constitutes an acid and a base. It was explained in chapter 4 that misconceptions, found as a result of quantitative analyses, would not be labelled as misconceptions until it was apparent from the interview protocols that the misconceptions persisted. The concept maps (chapter 4) show that misconceptions were found for all the participants, but at different nodes on their maps. Each misconception is listed with evidence to support its existence. (After the misconceptions are listed, one example of a modification of a potential misconception is given.)

1. Acids contain hydroxide ions.

   And what type of substances contains OH^-?

   Mabel: Acids.

   Acids?

   Mabel: Hydrochloric acid, sulfuric acid.

2. All acids are strong acids.

   Letty: What else? (laugh) No, I would say that an acid is strong.. It burns, it's like a chemical um..4..it can be a liquid or a gas and it ..10.

3. Concentrated is the same as strong.

   Letty: That Y is more concentrated like it is more acidic like it um is more powerful. I think it is more yeah like maybe the substance the acid is stronger.

   Now, would you say when something is more concentrated the substance is more powerful?

   Letty: No wait concentrated is yes concentrated is like when its more watery more solid I think.

So Y is more powerful than X.

Letty: Yes

4. Acids are poisonous.

Letty: I can just further that by saying acids do stick out in your mind because they are so much powerful. Everyone knows the acids are poisonous--they think of ammonia and bleach and things like that. Bases, to me, I don't picture anything in mind it just comes clear, you know. of these acids; gases sorry.

5. Acid rain is formed from water and chlorine or hydrogen gas.

Curly: Ah, give you the names, chlorine gas is produced. not strictly ah, gee so long ago, do you have a form of chlorine gas. I can't remember the name of it. Is some form of hydrogen produced?

6. Acids contain hydrogen in the gaseous state.

I did not say this before but more gas was produced when the hydrochloric acid reacted with the magnesium, why do you think more gas was produced?

Curly: Probably because there was a greater quantity of gas available inside the acid.

7. An acid and base reacts to form a solution.

Can you say what type of substance does C represent?

Curly: C represents, would it be a solution between A and B

8. A strong acid has a higher pH than a weak acid.

If you were asked to say what you think is the difference between a strong acid and a weak acid what would you say?

Curly: Oh, a strong acid would be more acidic meaning probably it has a higher pH and it reacts more greatly with other substances than a weak acid.

9. A gas is released when an acid and a metal reacts because heat changes the liquid to a vapor.

And can you say why the gas is produced? What causes it? You just add a solid to a liquid and then you see a gas; why did it happen?

Magnus: Um, well it must be heat of some kind to change it into a vapor.

10. When hydrochloric acid and magnesium react more gas is released than when acetic acid reacts with magnesium because the reaction is more violent.

Why was more hydrogen gas produced from Y?

Magnus: Um..5..um..3...I don't know, it reacts more violently.

11. When hydrochloric acid and magnesium react more gas is released than when acetic acid reacts with magnesium more hydrogen bonds need to be broken.

Why was more gas produced with the hydrochloric acid than with the acetic acid?

Ishmael: Um, because there were more hydrogen bonds to be be broken?

12. A strong acid reacts more slowly than a weak acid.

OK would you say acetic acid is a strong or weak acid since hydrogen took a long time to be evolved?

Delvin: I would say it is a strong acid because it took longer for the magnesium to break it down.

While some misconceptions were being confirmed others were being modified. Here is one example of a student changing a misconception during the interviews.

OK, it has a bad smell; and also bleach you have bleach classified as being an acidic substance. Why bleach is acidic? What about it.

Magnus: Well it isn't really..4..it isn't really gritty, it might be a base.

It might be a base?

Magnus: It has a smell, it has a slimy feeling.

It has a smell, a slimy feeling. So you want to change it from an acid to a base just because it has a slimy feeling.

Magnus: It takes a while to do the effect. You can't feel it.

So you are saying you want to change bleach from being acidic to basic.

Magnus: Yes.

Conclusions

The above discussion of the themes found in the qualitative data suggest that students have not learned the concepts set out in the Chemistry Curriculum Guideline. Several factors may have prevented the students from acquiring the concepts. Of these, the students' deficient prior knowledge and their applications of their everyday knowledge appeared most significant.

Evidence from the participants' protocols indicate students lacked knowledge of the concepts that they are generally expected to learn before instruction on acids and bases. For example, some students did not interpret information provided in equations and seemed not to know about the activity series of metals. Most of the participants knew of the everyday aspects of acids and bases and this knowledge may have influenced their tendency to use descriptive rather than scientific explanations in their answers. Of the acid-base concepts taught at Grade 11, the pH and ion concepts appear to be most significant if students are to understand acids and bases. The quantitative and qualitative data showed most students did not understand ions and the qualitative data showed students found difficulties with the concept of pH. Misconceptions have resulted because students have not grasped the concepts of pH and ions. In the light of these misconceptions, new or modified instructional strategies are necessary to allow students to grasp the concepts of pH, ions, and the other scientific concepts of acids and bases. Some suggestions are made for instruction in the final chapter.

Chapter 6

Summary, Findings, and Implications

This chapter summarizes the study with attention to the methods of the research, the principal findings about the participants' understanding of acids and bases, and the limitations of the study. Also discussed are the implications of this study for professional practice and suggestions for future research.

Summary

The study was conducted primarily to explore high-school students' understanding of acids and bases. Secondary purposes were: (a) to assess the validity of the multiple-choice test items; (b) to explore the relationships between the students' understandings and those intended by the Chemistry Curriculum Guideline; and (c) to assess the study's methods.

Because of the exploratory nature of the study, a combination of quantitative and qualitative methods was used in the investigation. Both of the quantitative and qualitative parts were based on a model concept map designed by the author. In the quantitative part, 34 Grade 12 students wrote a multiple-choice test that consisted of 10 OAIP items and 15 author-constructed items. And, in the qualitative part, eight of these Grade 12 students, selected on the basis of their Grade 11 achievement (high, medium, and low), participated in clinical interviews.

The analysis of the quantitative data in chapter 3 provided insights for the analyses of the qualitative data. Then, in chapter 4, the collective analyses generated case studies of three participants' understanding. Because these participants were drawn from the three levels (high, medium and low) of achievement in the multiple-choice test, their cases and concept maps were seen to be a reflection of all the Grade 12 students' understanding. The analysis reported in chapter 5 was developed from themes arising in the data.

Principal Findings

The multiple-choice test used in this study was found to be an adequately reliable and valid instrument to measure the students' understanding. An analysis of the test items showed the OAIP items posed greater difficulty to the students than the author-constructed items. The quality of each item was determined by its difficulty level, its discrimination index and its correlation with the total score. Although the items varied in quality, approximately equivalent numbers of OAIP items and author-constructed items were found to be "good."

Further analyses of responses to the multiple-choice test revealed that the students performed better on everyday knowledge items than on the other subscales. This finding confirmed what had been found in the pilot study. Also, after everyday items, the students performed best on the pH subscale, and found most difficulties with items about ions and bases. Some students' responses showed they had not fully grasped some of the concepts presented to them before instruction on acids and bases, such as equations. Students who lacked these concepts possessed a variety of misconceptions.

Analysis of the interview protocols confirmed much of what was found from analyzing responses to the multiple-choice test. For example, everyday and prior knowledge concepts continued to be significant factors influencing students' understanding. However, the pH concept emerged from the qualitative analysis as a significant factor leading to students' misconceptions on acids and bases.

Although the participants' performance in the test and in the interviews reflected their achievement level, their understandings (shown by their concept maps) were idiosyncratic. For example, Atlas (in the top level of achievement) seemed to use his own ideas to answer a question about the strength of acids. Ishmael (in the medium level of achievement) used the concepts as he understood them from the chemistry courses. Then, Letty (in the low level of achievement) correctly answered more questions about ions than Ishmael. Although Letty was in the low level of achievement she seemed to have a better knowledge of ions (a difficult subscale), than Ishmael.

The interview protocols provide instances where students produce contradictory viewpoints. There are also instances in which the participants give correct answers and change their views in subsequent statements. In contrast, there were cases where the participants modified their misconceptions.

The concept maps of those participants (Atlas and Ishmael) with fewest misconceptions show more linkages between the scientific concepts. These participants seemed to have a clearer understanding of ions and pH. The participants with more misconceptions verbalized few scientific viewpoints, and lacked knowledge of ions. And, though they seemed to know about pH, their inability to transfer this knowledge contributed to their misconceptions. It may be that students retained misconceptions that they held before instruction on acids and base in preference to the acid-base concepts. Also, their knowledge of everyday phenomena acquired before chemistry classes on acids and bases might have led to alternative ideas about acids and bases. According to Linn (1987):

> it appears that students constantly interpret new information based on their particular worldview. Their misconceptions therefore do not arise merely from failure to absorb information but rather from erroneous interpretations based on intuitive perceptions that must be overcome. (p. 197)

This may explain why most of the participants selected bleach and ammonia as acidic substances and why Crista thought tomatoes had a neutral pH.

Methodology

The combination of quantitative and qualitative methods was appropriate because of the exploratory nature of the study. By using a concept map to determine the selection of the multiple-choice items and the interview tasks, the content validity of the data increased. Also, the model concept map facilitated collective analyses of the data, and the presentation of the participants' concept maps. The study's reliability was strengthened by the combined analyses of the multiple-choice items and the interview data. Both analyses produced similar perspectives on the students' understanding of the acid-base concepts. For instance, except for the contribution to students' misconceptions by pH, the analyses of the interviews produced similar results to those obtained during the multiple-choice test. However, the clinical interviews elicited substantially more data and provided insights on how participants processed information.

Some aspects of this method have been used by other researchers to identify students' misconceptions. Treagust (1988) advanced arguments for the development and use of multiple-choice tests to evaluate students' misconceptions in science. Some of the steps he suggested for the design of diagnostic tests were: (a) pretesting the instrument, (b) using concept maps to define the content, and (c) conducting clinical interviews to facilitate the gathering of information.

Limitations

The small sample size, the construction of all the concept maps by the researcher, and the selection process for the sample are potential threats to the reliability and validity of the study.

The small sample size inevitably poses limitations to the generalizability of the study; but because of its exploratory nature, questions of generalizability are less important than the generation of valid descriptions of students' concepts. Concept mapping, mechanically recorded data, validated multiple-choice items, specific interview tasks (Interview-about-Instances, and

Demonstrate Observe Explain methods), and follow-up interviews all contributed to the reliability and validity of the study.

The author constructed the participants' concept maps by subtracting concepts and links from the model concept map. An alternative would have been to teach the students to construct their own maps. However, teaching students to construct their own maps might also lead to subjective interpretation. For this reason, students' concept maps were constructed by subtracting concepts that the participants did not voluntarily verbalize, or verbalized inaccurately, from the model concept map.

The threat to the study's reliability due to the selection process was reduced by the careful procedures used in the study. Care was taken to avoid ambiguity in language, and to allow each informant an adequate amount of time to respond to questions (Goetz & LeCompte, 1984). Follow-up interviews allowed the researcher to clarify ambiguities and to probe for richer students' understanding (West, Fensham & Garrard, 1985). Although the researcher drew from students who had moved to Grade 12, the results of the multiple-choice test and interviews are valid since understanding, not recall, was being probed. The warm-up exercises provided at the start of the interviews allowed relevant information to be brought into their short-term memory (Ericsson & Simon, 1984) from long-term memory. Rehearsal was minimized by varying the order of the interview tasks for each student.

Time and other constraints did not allow a longer probe for students' misconceptions. But, while it is plausible to assume that more interviews would have revealed more linkages in the students' concept maps, it is also plausible to assume that more misconceptions would have surfaced.

Implications for Instruction

The study's findings add to the information on students' misconceptions, give insights for the design and evaluation of instruction, and inform curriculum developers about curriculum modifications.

Misconceptions

Students' misconceptions were found in all areas of acids and bases. Those on everyday concepts seemed most significant because it is on those misconceptions that students build their knowledge of acid and bases. Common household products were incorrectly classified and although students knew of acid rain and antacids, few related this knowledge to chemistry. Some important findings of this study are: the students' deficiency of knowledge of everyday concepts and their misunderstanding of key concepts, such as chemical equations. The presence of these misconceptions indicate the need for modified instructional planning. Instructional planning must be accompanied by a search for a match between what the school wants the child to learn and what the child is inclined to learn. Reeve, Palincsar, and Brown (1987) commented:

> In settings of formal education, the goals and contexts of learning are usually not of the child's choosing...the learner is asked to acquire decontextualized bodies of knowledge for knowledge sake, in the service of no goal other than success at school. (p. 131)

Instruction

It is well documented that efforts to change students' conceptions will not be readily successful (Driver & Easley, 1978; Driver, Guesne & Tiberghien, 1985; Cros et al., 1986; and Treagust, 1988). Even second-year university students were seen to have gaps in their knowledge of the everyday life concepts, and the scientific concepts of acids and bases. Cros et al. (1988) found:

students do not perceive the relationships between the scientific notions they master and their application, not only in daily practice of chemistry but in everyday life. (p.335)

Any plan for improved instruction must be carefully implemented and adequate time allowed for for its success. First, students' prior knowledge should be determined by testing and careful questioning. Second, any decision about the instructional sequencing and alternative instructional strategies should be taken in the light of the students' prior knowledge. Two instructional strategies that have helped to reduce students' difficulties are:

1. Reciprocal teaching (Reeve et al., 1987); in this the teacher as the expert allows the student to build his or her confidence and gradually take responsibility for his or her learning.
2. Concept mapping (Novak & Gowin, 1984); students can be taught to make their own concept maps to keep track of their learning.

Finally, evaluation should be formative. Students' progress needs constant monitoring especially because of their individual differences, which leads to idiosyncratic understanding.

Future Research

The findings of the present study point clearly to the significance of further investigations of students' understandings of acids and bases. Appropriately, a multiple-choice test could investigate concepts of acids and bases held by a large sample of Grade 11 students, and the results compared with those of the present study. Also, a sample of students could be taught to design concept maps as a learning tool for acids and bases, and their performance on tests compared with that of students who had not used concept maps.

Further exploratory studies can be built on the methods and results of this study. For example, other unexplored chemistry topics such as solids could be investigated, using clinical interviews and concept maps. Also, similar methods could be used to investigate understandings of topics such as ions and pH at different levels of the school.

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Appendix A

Multiple-Choice Test

For each question there are four (4) suggested answers. Circle the letter corresponding to the answer that you consider to be most appropriate, on the answer sheet.

Time: 40 minutes

1. Select from the phrases below the one that best corresponds to your understanding of bases.
   a. A harmless substance
   b. A substance that is neutralized by acids
   c. A substance that has a bitter taste
   d. A substance that is used when cooking
2. Which one of the following groups of elements will all produce acidic solutions when their oxides are dissolved in water.
   a. Cl S Br N
   b. S P Ca Na
   c. N Mg K Ni
   d. Li Mg Na Cu
3. An element whose oxide will react with water to form a basic solution is
   a. Mg
   b. Cl
   c. P
   d. S

4. An acidic solution such as vinegar

   a. turns litmus paper blue

   b. has a salty taste

   c. has a sour taste

   d. feels slippery

5. In the neutralization reaction between strontium hydroxide, $Sr(OH)_2$, and perchloric acid, $HClO_4$, the products are water and

   a. $Sr(ClO_4)_2$ (aq)

   b. Sr_2Cl_2 (aq)

   c. Sr_2ClO_4 (aq)

   d. $SrClO_3$ (aq)

6. Bromothymol blue indicator is yellow in an aqueous solution of

   a. Sulfur dioxide

   b. Sodium oxide

   c. Magnesium oxide

   d. Sulfur

7. The net ionic equation for the reaction between aqueous sodium hydroxide, NaOH(aq), and dilute hydrochloric acid, HCl(aq), is

   a. $Na^+(aq) + Cl^-(aq) \rightarrow NaCl(s)$

   b. $H^+(aq) + OH^-(aq) \rightarrow H_2O(l)$

   c. $H(aq) + OH(aq) \rightarrow H_2O(l)$

   d. $HCl(aq) + Na^+(aq) + OH^-(aq) \rightarrow NaCl(aq) + H_2O(l)$

8. H_2 (hydrogen) is produced in an open container by the action of sulphuric acid (H_2SO_4) on zinc (Zn) according to the equation:

   $Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2(g)$

   this reaction goes to completion because

   a. chemical equilibrium is soon reached
   b. an insoluble solid is formed
   c. a gas is formed and escapes from the reaction vessel
   d. the acid used has a high boiling point.

9. Select from the phrases below the one that best corresponds to your understanding of acids.

   a. A dangerous substance.
   b. A substance that is neutralized by bases.
   c. A substance that is sour.
   d. A substance that is found in the stomach.

10. Which one of the following types of compound produces most hydrogen ions (H^+)?

    a. Strong acids.
    b. Strong bases.
    c. Weak acids.
    d. Weak bases.

11. A biochemist found that bromothymol blue (blue) solution turned yellow when a slice from a rat's stomach was dropped into it. Which one of the following statements best explains this phenomenon?

    a. The slice is normally a yellow color
    b. An acidic substance is present on the slice.
    c. Stomach cells are basic.
    d. Bromothymol blue is an unstable compound.

To answer question 12 and question 13, use the information in the table below:

Name of substance	Approximate pH
Tomatoes	4.2
Milk of Magnesia	10.5
Cabbage	5.3
Cocoa Cola	2.0
Washing soda	9.1
Carrot	5.0
Bicarbonate of soda	1.0
Lime juice	1.8
Toothpaste	8.5

12. Which substance is least acidic?

    a. Tomatoes

    b. Cabbages

    c. Carrots

    d. Limes

13. Which of the following substances will turn blue litmus red?

    a. Washing soda

    b. Ammonia solution

    c. Milk of Magnesia

    d. None of the above

14. A solution which contains an equal number of hydrogen ions and hydroxide ions is

    a. An acidic solution

    b. A basic solution

    c. A neutral solution

    d. A solid solution.

15. Milk of Magnesia is an example of an antacid because

    a. It does not react with acids.

    b. It neutralizes acids.

    c. It is a type of acid.

    d. It forms an acid when added to water.

16. A colorless solution was tested and found to have a pH equal to 10.

    a. It is acidic.

    b. It contains more hydrogen ions (H^+) than hydroxide ions (OH^-).

    c. It is neutral.

    d. It contains more hydroxide ions (OH^-) than hydrogen ions (H^+).

17. Which of the following is NOT a property of acids

    a. A sour taste

    b. A pH greater than 7

    c. An ability to turns blue litmus red

    d. A corrosive nature

Use the information below to answer questions 18 and 19:

Acid rain is produced when sulfur and nitrogen containing compounds burn in industry and are released into the atmosphere.

18. Which one of the reactions below is NOT likely to occur during the formation of acid rain?

   a. $SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$

   b. $2H_2S(g) + 3O_2(g) \rightarrow 2SO_2(g) + 2H_20(l)$

   c. $H_2O(l) + NO_2(g) \rightarrow HNO_2(aq) + HNO_3(aq)$

   d. $CO_2(g) + H_2O(l) \rightarrow H_2CO_3\ (aq)$

19. One of the following statements about acid rain is false. Which is it?

   a. It causes irritation of the respiratory tract.

   b. It has harmful effects on buildings.

   c. It enriches the soil.

   d. It adversely affects the reproductive systems of fishes.

20. Which of the following elements will displace hydrogen most readily from dilute sulfuric acid solution?

   a. Gold

   b. Silver

   c. Aluminum

   d. Calcium

21. Some aqueous solutions are strongly basic because

   a. They contain a high concentration of metallic ions

   b. They contain a high concentration of hydronium ions

   c. They hardly dissociate into their constituent ions

   d. They contain a high concentration of hydroxide ions.

22. Select the acid-base reaction among the following reactions.

    a. $AgNO_3(aq) + NaCl(aq) \rightarrow AgCl(aq) + NaNO_3(aq)$

    b. $Br_2(g) + 2KI(aq) \rightarrow 2KBr(aq) + I_2(g)$

    c. $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(l)$

    d. $2NaOH(aq) + CaCl_2(aq) \rightarrow Ca(OH)_2(aq) + 2NaCl(aq)$

23. Dilute bases have all EXCEPT one of the following properties in common. Identify the EXCEPTION

    a. They feel slippery

    b. They turn bromothymol blue yellow

    c. They neutralize acids

    d. They turn red litmus paper blue.

24. 20 ml. of nitric acid (HNO_3) was added from a burette to 20ml. of potassium hydroxide (KOH) in a volumetric flask. When two drops of litmus solution were added to the mixture in the flask a blue coloration was produced. Which of the following statements is NOT correct?

    a. Nitric acid is more concentrated than potasssium hydroxide.

    b. After mixing the flask contains at least 40 ml. of solution.

    c. Potassium hydroxide is more concentrated than the nitric acid.

    d. Litmus solution is used as an indicator.

25. A piece of magnesium ribbon was added to a beaker containing dilute hydrochloric acid. Which of the reactions described below will occur?

    a. Vigorous reaction and evolution of a greenish-yellow gas.

    b. No visible reaction.

    c. A vigorous reaction and evolution of a colorless gas hydrogen.

    d. A reaction of the metal but no evolution of gas.

Appendix B

Interview Tasks

Four sets of tasks were given to the participants. The first was based on the "Demonstrate Observe and Explain method" (Champagne, Klopfer & Anderson, 1985). The other three were based on the "Interview-about-Instances" (Gilbert, Watts & Osborne, 1985). Both of the methods have been used successfully to test physics concepts and were modified to accommodate the testing of acid-base concepts.

As previously explained, the first set of tasks were modified from the "Demonstrate, Observe and Explain" method. For this method the relevant phenomena are demonstrated to the participants who observe and give reasons (explain) for their observations. Because the substances used in the present study are well known, only a list of names was given. First the participants were required to classify the substances as either acidic or basic. Then, they selected one of the substances from each group and answered several questions.

Classification of Acidic and Basic substances (DOE)

Card 1

You are given the following list of substances:

Toothpaste, Milk of Magnesia, baking soda, vinegar, washing soda, household ammonia, bleach, Saniflush, milk, apples, soft drinks, tomatoes, coffee, tea, lemon juice, desert soil, forest soil. These substances are commonly found in and around the home. Identify the ones you are familiar with and try to classify them as either acidic or basic substances.

Card 2

Select one acidic substance from your list and tell me something about:

1. Its appearance;
2. Its usage;
3. The way its acidity influences its usage.

Card 3

Select one basic substance from your list and tell me something about:

1. Its appearance;
2. Its usage;
3. The way its basic nature influences its usage.

Card 4

1. What do you understand by the term pH?
2. Can you name a substance that has a pH of 7?

Card 5

1. What is H^+?
2. What type of substances contain H^+?

Card 6

1. What type of substances contain OH^-?
2. How is H^+ and OH^- related to pH?

Interview about Strength of Acids (IAI--1)

Card 1

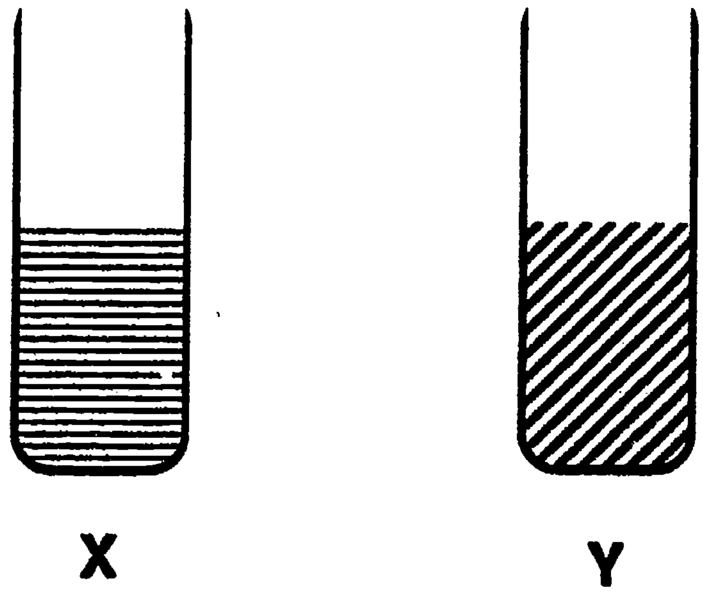

Figure 10. Reactions of a weak and a strong Acid with Magnesium

X and Y are acids of the same concentration. When a little magnesium powder was added to X, 30 seconds passed before any gas appeared. When a little magnesium powder was added to Y there was a rapid evolution of gas almost immediately.

a. Why do you think bubbles of gas appeared more quickly in Y than in X?

b. Can you say why this gas was produced?

Card 2

X is acetic acid, Y is hydrochloric acid.

1. Are you familiar with these names?
2. Do you wish to change anything you said previously, now that you know the identities of X and Y?

Card 3

1. What type of substance is magnesium?
2. Can you name other substances that produce similar reactions that magnesium had with X and Y?

Card 4

1. Where did the gas (hydrogen) come from?
2. Why was more gas produced when hydrochloric acid reacted with magnesium?

Card 5

1. Would you say acetic acid is a strong or weak acid? Why?
2. Can you name three or more bases?

Interview about Neutralization (IAI--2)

Card 1

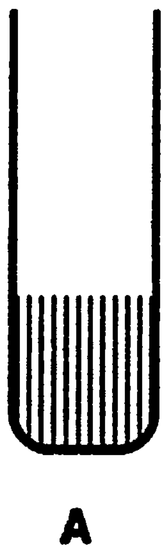

Figure 11. Test Tube containing solution A

A is a colorless solution whose formula is HCl. The present room temperature is 25C, and the pH of A is 1.5.

a. What type of substance is A?

b. What information above allows you to classify A?

c. What is the name of A?

Card 2

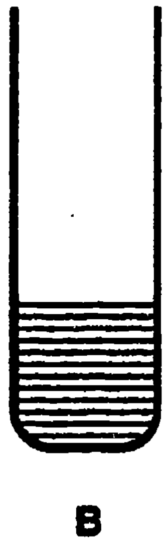

Figure 12. Test Tube containing solution B

B is a colorless solution whose formula is KOH. The room temperature is 25C and the pH of B is 12.

a. What type of substance is B?

b. What information given allows your classification of B?

c. What is the name of B?

Card 3

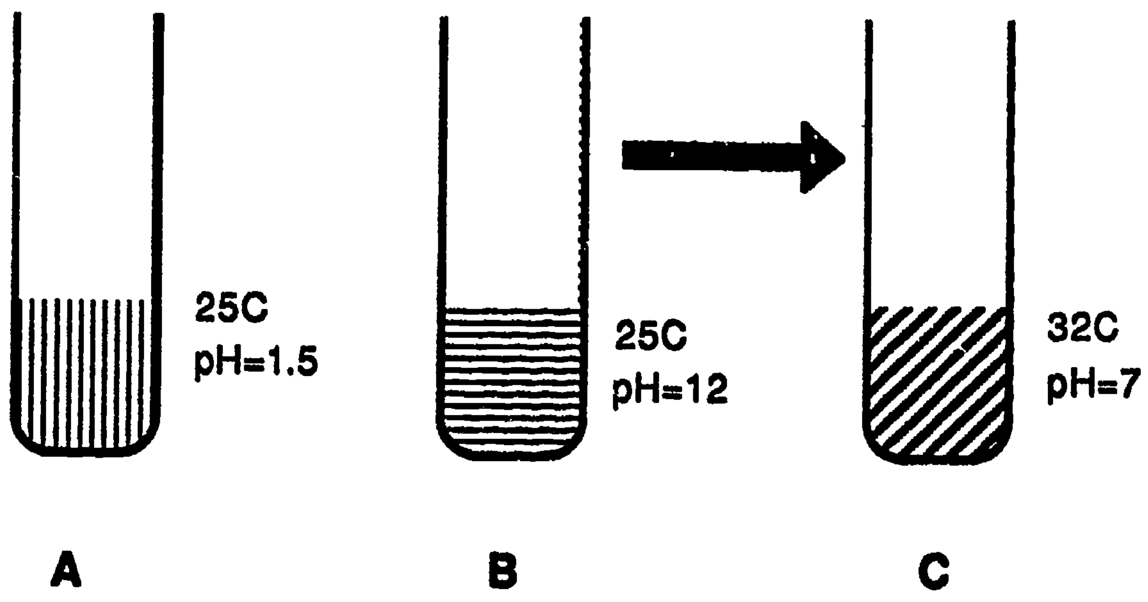

Figure 13. Products of a Neutralization Reaction

When A and B are mixed C is produced.

a. Can you say what substance (s) C represents?

b. Is there anything significant about the temperature of C?

c. Is there anything significant about the pH of C? Can you explain?

Card 4

A + B → C

HCl + KOH →

1. Can you complete the equation?
2. If so, please explain what is happening.

Card 5

$H^{+}.Cl^{-}$ + $K^{+}.OH^{-}$ →

1. Can you complete the above equation?
2. Which of the above ions are spectator ions?

Everyday Acid-Base Phenomena (IAI--3)

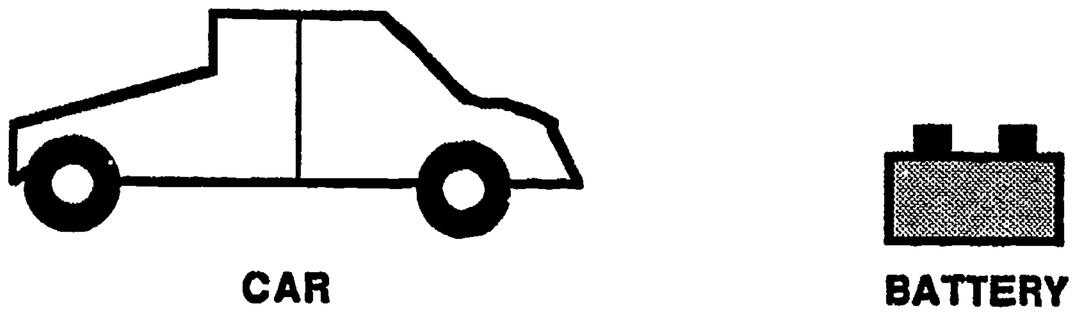

Figure 14. A Car and a Battery

Card 1

a. Of what importance is the battery (to the car)?

b. Can you name the important chemical that is used in the battery?

c. Why is this chemical important?

d. Can you write the formula for the substance?

Card 2

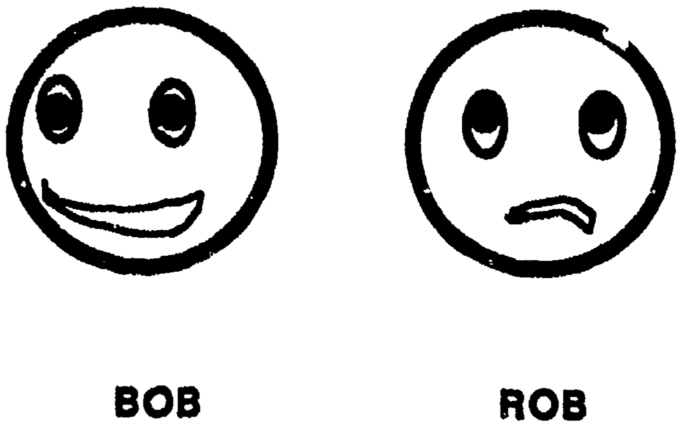

Figure 15. Rob has problems--Acid Stomach

Bob and Rob are good friends. Rob is unhappy, in pain. Rob has bad eating habits and suffers intensely with stomach pain. Bob has no such problem.

a. The doctor says Rob has "acid stomach." What do you understand by this?

b. What type of medicine is the doctor likely to prescribe for Rob?

c. Can you say how the medicine will work?

d. Can you say what type of substance is this medicine?

Card 3

Each participant was shown the three pictures (Figures 16-18) and asked the following questions:

1. Can you name (or write formulae for) two gases produced when the fossil fuels burn?
2. Can you name (or write formulae for) two acids produced from these gases?
3. Can you give a brief description of what happens from the time fossil fuels are burned to when acid rain is found in a lake?
4. Can you write the equations for these reactions?

Other Tasks

During the first interview, each student was asked to verbalize how he or she would explain to a friend, the nature of (a) an acid, and (b) a base.

At the end of the follow-up interview, each student was asked to say five words or phrases that came into their minds when they thought of (a) an acid, and (b) a base.

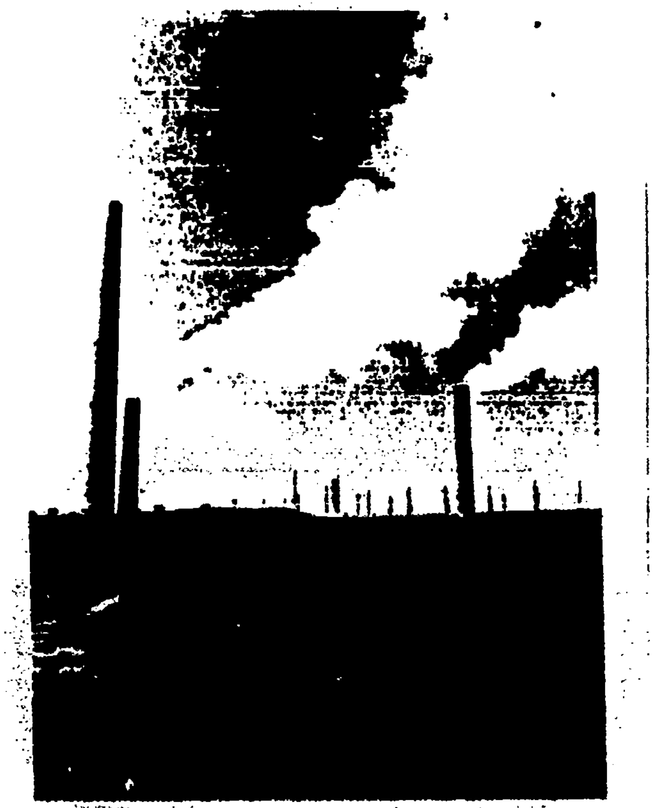

Figure 16. Fossils Fuels Burn Releasing Gases that produce Acid Rain

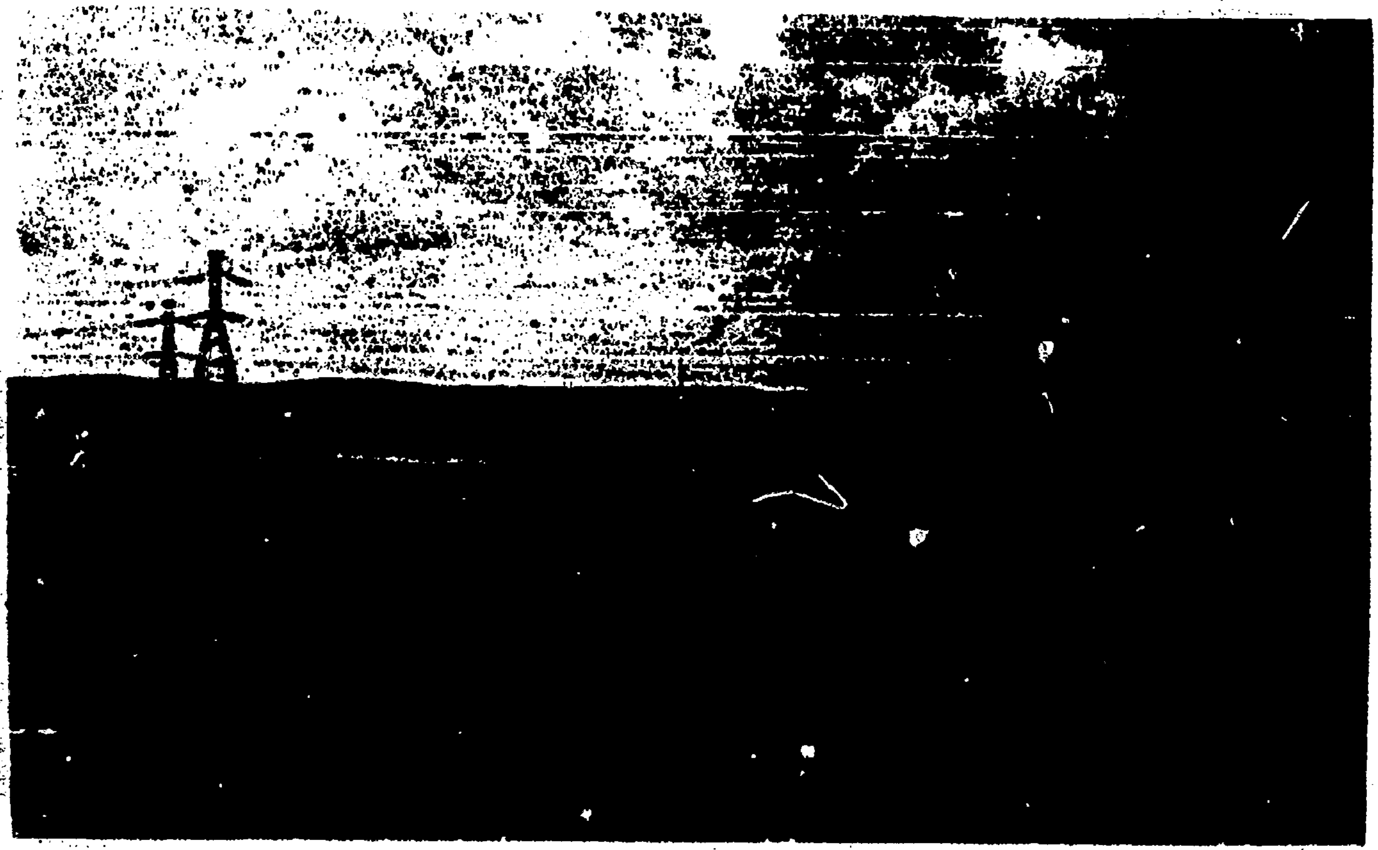

Figure 17. Acid Rain Destroys Vegetation

Figure 18. Acid Rain Kills Living Organisms in Rivers