STUDENT DIFFICULTIES WITH
VOLUMETRIC ANALYSIS

by

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We accept this thesis as conforming
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Abstract

The study was designed to investigate the difficulties that grade 12 chemistry students have with volumetric analysis. In the first part of the study, a model of performance on volumetric analysis calculations was developed from the integration of two theoretical perspectives of intellectual performance, namely, the proportional reasoning schema in Piaget's theory and the cumulative learning theory of Gagné. This integrated model hypothesized some relationships among the variables: direct proportional reasoning, inverse proportional reasoning, prerequisite concepts and performance on volumetric analysis calculations. The second part examined specific conceptual and manual difficulties that the students have with volumetric analysis.

Tests developed in a pilot study were used to measure direct proportional reasoning, inverse proportional reasoning, knowledge of subsumed concepts and performance on volumetric analysis calculations. The first three measures were administered to subjects enrolled in the grade 12 chemistry course prior to the teaching of the volumetric analysis unit. After the teachers had taught the volumetric analysis unit, a test measuring performance on volumetric analysis calculations was administered to the students. The final sample size was 328. After administration of the tests, a subsample of 47 subjects was interviewed on a titration task.
The test data were analyzed using path analysis techniques. The psychometric properties of the tests were assessed. The internal consistency estimate of reliability for each of the tests was above 0.75.

The interview data and the written work of the subjects on the volumetric analysis calculations were analyzed using qualitative procedures (e.g. categorizing the frequency of response patterns or conceptual errors). The relationship between prior number of titrations performed and performance or volumetric analysis calculations was analyzed using correlational analysis.

The evaluation of the proposed integrated model revealed that the performance of subjects identified as using algorithms without understanding could be adequately explained by a trimmed integrated model in which direct proportional reasoning and inverse proportional reasoning were assumed to have negligible direct influence on prerequisite concepts and volumetric analysis calculations, respectively. The evaluation of the proposed integrated model for subjects identified as using algorithms with understanding revealed that a trimmed integrated model in which direct proportional reasoning was assumed to have negligible direct effect on prerequisite concepts and volumetric analysis calculations provided a reasonable explanation of their performance.

The analysis of the subjects' calculations on the items in the volumetric analysis instrument revealed a number of conceptual errors (e.g. indiscriminate assumption of 1:1 mole ratios) made by the subjects.
The analysis of the manipulatory skills of the subjects during the interview revealed that while some skills seemed to be adequately developed, other important skills seemed to be lacking.

The analysis of the students' understanding of concepts involved in an acid-base titration revealed that the concepts of pH and indicator behaviour as well as the use of certain scientific terminologies such as endpoint were not well understood.

The analysis of the approaches used by the subjects to calculate the concentration of the acid solution from their own data, during the interview, revealed that two main approaches - the Proportional Approach and the Formula Approach - were used by the subjects in their solution. However, the Formula Approach was used by a greater proportion of the subjects.

Several implications for chemical education in the secondary school were inferred from the interpretation of the results. Such implications include the development of different instructional strategies reflecting the different path models for students who use algorithms with and without understanding.
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CHAPTER I

INTRODUCTION

Background to the Problem

In recent years science education researchers have been called upon to increase the amount of research on the difficulties students have with specific science concepts (Shulman and Tamir, 1973; Driver and Easely, 1978; Levine and Linn, 1977). Kuhn (1979) has suggested that some of the problems science educators encounter in applying psychological theories to their specific areas reflect the ambiguities inherent in the theories themselves. It has been noted that the simultaneous application of more than one psychological theory may remove some of the problems encountered when they are applied separately (Sticht, 1971; Griffiths, 1979) in investigating children's difficulties with school concepts. As such, there exists a need for research that is science concept specific and that attempts to integrate more than one psychological theory.

The present study, in keeping with the positions stated above, examined a persistent problem in high school chemistry, namely, the difficulties that students experience
with volumetric analysis. The choice of volumetric analysis grew from the writer's experience in teaching this aspect of the introductory chemistry course in high school and by the concern expressed by other chemistry educators (Herron, 1975; Wheeler and Kass, 1977). Both chemistry teachers and researchers have been aware of the apprehensions students have and the difficulties they encounter when doing volumetric analysis calculations (Duncan and Johnstone, 1973; Johnstone, Morrison and Sharp, 1976). Although no rigorous study has been done to identify factors contributing to students' difficulties in performing computation problems in volumetric analysis, these difficulties have been attributed to the task components (i.e. content) or structure inherent in the task (Duncan and Johnstone, 1973; Herron 1975; Wheeler and Kass, 1977). If those task components or structure which contribute to the difficulties that students encounter in solving such tasks could be identified, then it may be possible to design teaching strategies which would help to alleviate these difficulties. Also, isolation of the sources of difficulty may help in understanding how these sources independently and collectively affect processing abilities of students and how students come to solve problems involving volumetric analysis.

Consider the following typical volumetric analysis problem: 25 mL of 1 M solution of hydrochloric acid neutralizes 20 mL of sodium hydroxide solution. What is the concentration of the sodium hydroxide solution?
In solving such a problem a student may reason:

"First, I need to find the stoichiometric relation between HCl and NaOH. This is 1:1. Therefore, the number of moles of HCl in the reaction would be equal to the number of moles of NaOH in the reaction. Since I can calculate the number of moles of HCl from its concentration and volume, I can determine the concentration of the NaOH solution from the equality."

Such reasoning involves:

a) the recognition of direct proportionality between the stoichiometric coefficients and the number of moles of the reactants;

b) the recognition of inverse proportionality between concentration and volume of the reactants; and

c) the understanding of subordinate content (i.e. concepts and rules) such as the mole, balancing of chemical equations, and calculation of amount of reactants from stoichiometric equations.

The direct and inverse proportionality constitute the structural components of the problem while the subordinate concepts and rules constitute the content of the problem.

Although all three requirements, taken together, may be necessary for a subject's understanding of the problem, they may not all be required for a subject to successfully solve the problem. This is because subjects may perform the task without showing the understanding laid out above by resorting to the use of formulas such as

\[
\frac{C_{HCl}}{V_{HCl}} \cdot \frac{V_{HCl}}{a} = \frac{C_{NaOH}}{V_{NaOH}} \cdot \frac{V_{NaOH}}{b}
\]
where C and V represent the concentration and volume of the solutions, and a and b are the stoichiometric coefficients (or mole ratios) for the acid and the base, respectively. This alternate solution of using a memorized algorithm has been noted in studies of other areas in chemistry which have reported the predominant use of formulas without adequate understanding (Chappetta, 1974; Smith, 1978). Such lack of understanding may be seen in the choice of stoichiometric coefficients. To further clarify this issue, subjects in the present study were identified who performed volumetric analysis calculations using the correct coefficients and those who assumed unit values for the coefficients regardless of the actual reacting coefficients.

Analytic Orientations:

Chemical problems of the type outlined above have generally been analyzed only in terms of the operational structures demanded by the problem (Herron, 1975; Ingle and Shayer, 1971; Mealings, 1969) using Piaget's theory, without giving adequate consideration to contextual variables such as the content of the problem. Currently, there seems to be a growing concern over the sole reliance on operational structures in analyzing student's performance in problem solving situations. Some of these concerns were expressed as a reaction to the differential performance of experimental subjects on tasks requiring equivalent logical structures (Brown and Deforges, 1977; Smedslund, 1977). As a result
many researchers have called for an analysis of the content of the task in addition to the operational structures involved (Abramowitz, 1975; Driver and Easely, 1978; Lunzer, 1965; 1975). Others have suggested that more attention be paid to the subject's familiarity with the task (Lovell, 1971a; 1973; Berzonsky, 1971). But as Johnson-Laird, Legrenzi and Legrenzi's (1972) study indicated, familiarity may be nothing more than knowledge of the content. To this end, studies have been done which attempted to examine the effect of the content on performance (e.g. Griffiths, 1979) using Gagne's cumulative theory. In the present study, two theoretical frameworks -- Piaget's theory of intellectual development (Inhelder and Piaget, 1958) and Gagne's (1977) cumulative learning theory -- were taken as the basis for developing an integrated model in an attempt to identify the influences of structure and content upon performance on volumetric analysis problems.

The structure -- direct and inverse proportionality -- and the content -- the subsumed prerequisite concepts -- constituted the predictor variables in the study. The dependent variable in the study was the student's performance on a set of volumetric analysis problems. A subject who possessed all three requirements, namely direct proportionality, inverse proportionality, and subsumed concepts, was expected to solve the volumetric analysis problems successfully. In contrast, subjects missing any of these skills were expected to have some difficulties with the problems. In examining the interrelationships among these variables, path analysis was employed.
Apart from the development and statistical validation of the above relationships, the study also examined three other areas relevant to gaining further understanding of students' difficulties with volumetric analysis. One of these involved the identification and classification of the conceptual errors made by subjects when solving the volumetric analysis calculation problems.

The second area was an examination of the laboratory skills and conceptual understanding which students displayed when doing a practical titration task. Furthermore, an analysis was made of the types of strategies used by these students when they applied the results of their titration to a set of volumetric analysis problems.

The third area involved an investigation of the relationship between performance on volumetric analysis calculations and the number of laboratory titrations performed.

Three different analytic techniques were used in examining these concerns. These were respectively, (1) the examination of students' written work for the type and frequency of errors made, (2) the use of clinical interviews in a titration experiment and (3) the use of correlational analysis.

These investigations provided: (1) additional insight into the difficulties students have in volumetric analysis, and (2) data to enrich the interpretation of the results from the path analysis.
**Definition of Terms**

Volumetric Analysis: the process whereby the amount of a chemical substance in a given sample involved in a quantitative chemical reaction is determined with the aid of a chemical indicator in a process called titration. In volumetric analysis, the amount of one of the reactants is unknown. The objective therefore is to determine the mass or concentration of the desired substance in a sample whose quantitative composition is unknown (Toon and Ellis, 1973).

Volumetric Analysis Calculation or Problem: the determination of the concentration or mass of one chemical substance from the known concentration of the other substance in an acid-base reaction. In the present study, performance on this variable was measured by the 'Volumetric Analysis Test' (see Appendix A).

Direct Proportionality Reasoning: two variables so related that their ratio is constant, are directly proportional to each other (Vance, 1962). In this study, direct proportionality was measured with the first subtest of the 'Classroom Proportionality Test' (see Appendix B).

Inverse Proportionality Reasoning: two variables so related that their product is a constant, are inversely proportional to each other. In the present study, inverse proportionality was defined in terms of scores on the second subtest of the 'Classroom Proportionality Test' (see Appendix B).

Subsumed or Prerequisite Concepts: concepts hypothesized to
be necessary for understanding volumetric analysis problems. These subsumed concepts are, therefore, integrally related to volumetric analysis problems in that it is hypothesized that such problems cannot be understood if the subsumed concepts are not available to the subject. In this study, the subsumed prerequisite concepts included essentially the concepts identified by Gower, Daniels and Lloyd (1977a) to be necessary for solving volumetric analysis calculations. These concepts are the mole, gram/mole conversions, balancing and interpreting equations, calculating relative mass of reactants and products from equations, converting a solution from one concentration to another, and calculating the concentration of solutions from the mass of the substances. Using Gagné's cumulative model, these concepts were arranged in a hierarchical order even though, as will be shown in Chapter II, the order was not particularly relevant in this study. For the purposes of this study, students' knowledge about the subsumed prerequisite concepts was derived through content analysis of volumetric analysis calculations using the Subconcepts Test (contained in Appendix C) completed by the students.

Reasoning Strategy: a plan, or strategy for generating orderly relationships out of experience, in other words, for solving problems and generating new knowledge. Reasoning strategies operate in problem solving as part of one basic process which has, as its aim, the organization of experience into meaning-
ful systems of objects, events, and situations. They are in a sense explicit guides to problem solving (Lawson, 1979). The reasoning strategies of interest in the present study were the procedures or approaches used by subjects as they verbalized their solutions to a volumetric analysis problem in an interview situation.

Conceptual Error: an error in reasoning or a misconception displayed by a subject in his/her calculation as he or she solved a volumetric analysis problem.

Algorithm: rule or formula employed by individuals as aids in solving problems or making a set of data meaningful. In this study, formulas and rules involved in stoichiometric calculations were classified as algorithms.

Statement of the Problem

The present study integrated aspects of two theoretical perspectives of intellectual performance, namely, the proportional schema in Piaget's theory and the cumulative learning theory of Gagné, into a model to account for an individual's performance of volumetric analysis calculations. As will be argued in Chapter II, Piaget's theory suggested that direct proportional reasoning precedes inverse proportional reasoning and that both inverse and direct proportional reasoning influence achievement on certain prerequisite chemical concepts. It further suggested that inverse proportional reasoning influences performance on volumetric
analysis calculations. The cumulative learning theory of Gagné suggested that the prerequisite concepts or content influence performance on volumetric analysis calculations. Taken together, these interrelationships suggested the integrated model represented in Figure 1.

The primary purpose of the study was, therefore, to test the validity of the integrated model proposed in Figure 1, thereby gaining greater understanding of the relative influence of direct proportionality, inverse proportionality, and subsumed concepts on volumetric analysis performance.

A secondary purpose of the study was to examine the following issues related to students' difficulties with volumetric analysis:

a) the conceptual errors made by students in their calculations,
b) the subjects' laboratory techniques and understanding of the concepts involved in a titration experiment, and
c) the relationship between the number of prior laboratory titration performed by the subjects and their performance on volumetric analysis calculations.

Exploratory in nature, the main aim of these investigations was to provide a detailed view of the subjects' difficulties with volumetric analysis.

Research Questions

The general concerns outlined above were grouped into two distinct but related groups of questions according
Subsumed Concepts

Figure 1: Proposed Integrated Model of Performance on Volumetric Analysis Calculations*

* A fuller explanation and justification of this model including a description of the symbols used is given in Chapter Two.
to whether they fell under the primary purpose of the study (i.e. model testing) or the secondary and exploratory section of the study.

The first question which related to the testing of the model was:

Question 1:
Is the arrangement of variables represented in the integrated model valid according to the application of path analysis? Specifically, does the integrated model closely mirror the subjects' performance on the tests?

This question related to the determination of the validity of the model as a whole through: (i) the use of model comparison techniques and (ii) examination of the significance of each of the paths connecting pairs of variables (that is, the hypothesized influence of one variable on another).

As suggested in the literature, students who use certain algorithms in their solutions to chemical problems may do so either with or without understanding of the algorithm (Chiappetta, 1974; Smith, 1978). Thus, an attempt was made in this study to identify these two groups of students through the form of their responses to the Volumetric Analysis Test. Students who used algorithms indiscriminately, (e.g. they used a 1:1 mole ratio when it was not applicable) formed one group while those who used algorithms discriminately (e.g. they used a 1:1 mole ratio with an understanding of when to apply it) comprised the second group. It was
hypothesized that since these groups of subjects might respond differently to the tests used in the study, the proposed model might fit the data for one group more closely than for the other. Hence, the second major question addressed was:

Question 2:
Does the integrated model account for the observed data for the two groups of subjects to the same extent?

The statistical hypotheses for the above research questions will be stated in Chapter IV.

The research questions addressed in the secondary part of the study were:

Question 3:
What conceptual errors are made by students on the Volumetric Analysis Test?

Question 4:
What practical laboratory skills do subjects display in a titration experiment?

Question 5:
What difficulties do subjects have with concepts involved in an actual titration experiment?

Question 6:
What are the different approaches used by the subjects in solving a volumetric analysis problem?

Question 7:
Is the number of laboratory titrations performed related to students' performance on the Volumetric Analysis Test?
The third question sought to identify the errors made by the subjects as they solved the problems on the Volumetric Analysis Test. The next three questions explored the type of understanding that subjects bring into actual titration situations. The manipulatory behaviour (i.e. practical skills) of the subjects as well as their understanding of the concepts involved in titration (e.g. pH, indicators, terminology) were the subjects of the fourth and fifth questions respectively. The sixth question examined the approaches used by the subjects while doing a Volumetric Analysis problem.

In the seventh question, the relationship between prior involvement in performing titrations and performance on volumetric analysis calculations was examined. The degree of involvement was defined as the number of laboratory titrations done since grade eleven.

**Overview of the Study**

In this chapter, the background, definition of terms and the research questions posed in the study were described. In Chapter II, relevant literature related to the present study are reviewed. In particular, literature related to the content of a task and the intellectual structure (i.e. proportional reasoning) demand by a task are reviewed. Also the empirical and theoretical underpinnings of the hypothesized model are discussed.

In Chapter III, the data collection instruments and the pilot study are described. Following this, the
procedures employed in the main study for data collection and analyses are presented in Chapter IV. In Chapter V, results are reported and discussed for the research questions related to the testing of the model. The results for the questions posed in the secondary part of the study are then presented and discussed in Chapter VI. Finally, in the last chapter, Chapter VII, a summary of the study together with the theoretical and educational implications are presented.
CHAPTER II

REVIEW OF THE LITERATURE

Introduction

The focus of this study - the effect of underlying structure and content on performance - suggests the review of literature related to these two areas. In this chapter, the proportional reasoning schema in Piaget's formal operational theory are described and related to the problem at hand. Following this, Gagne's cumulative model are summarized. Studies employing the structure and/or the content as the explanatory construct are discussed. The studies reported in the literature are then used to construct an integrated model of performance on the volumetric analysis calculations. Finally, studies related to the secondary part of the study are discussed.

The Proportionality Schema In Piaget's Model of Adolescent Reasoning

Piaget postulated two general conceptual acquisitions which characterize adolescent thinking (or formal operations in Piaget's terminology). These are:
(a) propositional logic, and (b) formal operational schemata. This is clearly stated by Inhelder and Piaget (1958) as follows:

..... formal thinking (i.e. adolescent reasoning) makes its presence known not only by the constant utilization of the sixteen binary propositional operations and some ternary or superior combinations which derive from them but also by the sporadic elaboration of some concepts or schemata which are inaccessible at the concrete level ..... (p. 308)

Since a comprehensive review of the formal stage is not intended here, attention will be focussed on the formal operational schemata while the propositional logic will only be referred to where it serves to clarify Piaget's explanation of the former (i.e. the schemata).

According to Inhelder and Piaget (1958, pp. 308-309), the operational schemata constitute general concepts which manifest themselves at the formal level when the subject is faced with certain kinds of data, but which do not manifest themselves otherwise (p.308). They are general in the sense that they reappear in many different problems or are applicable in the most diverse situations. In the view of Inhelder and Piaget, these general concepts are not discovered in the objects themselves but are abstracted or deduced by the subject from his own 'operational structures', and that all of these concepts "show some relationship to the lattice or group structures, and several of them to the INRC group of inversions and reciprocities" (pp. 309-310).

These schemata or general concepts include combinatorial reasoning, proportions, double systems of
reference, mechanical equilibrium, probabilities, correlations, multiplicative compensations, and forms of conservation which go beyond direct empirical verification.

The following section will present a summary of Piaget's explanation of the proportionality schema.

Proportion is a relation of one variable to another; it is the equivalence of two relations or ratios. Thus in solution chemistry, the relation: concentration = moles/volume, is a proportional relationship. Proportional reasoning therefore involves the ability to use proportions and ratios.

Inhelder and Piaget (1958, p. 317) view the proportional schema as having two aspects – logical proportions and metrical proportions. They point out that logical proportion precedes metrical proportion. That is, logical proportion, which expresses the compensation between two heterogeneous factors such that an increase in the value of one gives the same result as an increase or decrease in the value of the other (in qualitative terms), is achieved earlier than metrical (or numerical) proportion which expresses these same compensations in quantitative terms. They noted that whereas with logical proportion, compensation may be additive or multiplicative, metric proportionality involves only multiplicative compensations. Inhelder and Piaget point out that this accounts for the "initial tendency of the child to look for proportionality in the equality of additive differences" (1958, p. 223). They also stated that this compensation, which forms an important aspect in the acquisition of proportion, derives
directly from the idea of reciprocity.

The position that proportion is a second-order operation is clearly expressed by Inhelder and Piaget, "In this sense proportions presuppose second degree operations and the same may be said of propositional logic itself, since interpropositional operations are performed on statements whose intrapropositional content consists of class and relational operations" (1958, p. 254). Inhelder and Piaget state further that the acquisition of the operational schema of inverse proportion presupposes an understanding of both reciprocity (that is, compensation by equivalence) and proportions, a feat which is achieved only during late adolescence. However, Piaget points out that problems of direct proportionality as in the experiments on the notion of similar triangles (Piaget, 1957) and problems of simple reciprocity as in the problem of communicating vessels (Inhelder and Piaget, 1958, pp. 133-147) tend to be solved during early adolescence (that is, around ages 11 and 12). This means that relations of inverse proportionality come later than those of direct proportionality (Rogers, 1977). Piaget's (Inhelder and Piaget, 1958) interpretation of the essential mechanism underlying the understanding of problems of reciprocity and proportions can be presented in two stages.

First, Piaget showed that wherever two physical systems of actions are reciprocally related to one another, any action may be cancelled either by executing the opposite action, i.e. performing the inverse action within the same
action system - a process called Inversion or Negation - or executing an action within the related action system - a process called Reciprocity - to obtain similar result.

Thus using the equilibrium between communicating vessels as an example, they showed that the action of lowering the level in one vessel by raising the vessel while leaving the other vessel undisturbed may be annulled either by lowering the same vessel, i.e. Negation - performing the inverse action within the same action system - or by raising the other vessel, i.e. Reciprocity - executing an action reciprocal to that of the original action but in related vessel. Since each vessel can be raised and lowered this produces four possible actions for the two vessels as a whole. Piaget further points out that these two forms of reversibilities i.e. Negation (or Inversion) and Reciprocity, which represent separate transformations during the preadolescent stage become integrated into a single system at the 'formal stage'. Thus, irrespective of the action taken as the starting point for these transformations, the interdependence of inversion and reciprocity continue to hold. Thus, in a logical sense, the four actions (or transformations) in the system of communicating vessels, constitute a group.

The group nature of the four actions can be shown (according to Lunzer, 1965) by assuming any of the actions to be a point on a vector where the vector represents the particular type of action (disregarding the distance, i.e. the magnitude, on it). If one of these four vectors is chosen as
the starting point and called $I$ (identity operator), then the vector representing its exact opposite can be called $N$ (negation, raising or lowering the vessel), $R$ (reciprocity) which has similar effect to $N$ can stand for the third vector and the fourth vector which is the exact opposite of $R$ can be called $C$ (correlative). The $I, N, R,$ and $C$ operations therefore constitute a group of transformations which describe the relations between the four vectors and has the following multiplicative table.

\[
\begin{align*}
I^2 &= N^2 = R^2 = C^2 = I \\
IR &= RI = R; \ IN = NI = N; \ IC = CI = C \\
NR &= RN = C \\
CR &= RC = N \\
CN &= NC = R \\
IN &= RC \\
NRC &= I
\end{align*}
\]

This group - $INRC$ - is isomorphic to a well-known mathematical group called the four group.

Although, the $INRC$ group can be seen to be connected to the physical system, in the second stage of his interpretation, Piaget argued that this occurs as a result of the adolescent's use of propositional logic. Thus, he tried to show the interconnection between the $INRC$ connected with the physical system and the isomorphic group connected with the propositional logic. It is this aspect of his theory which has raised a number of criticisms.
According to Piaget, for two elementary propositions, P and q, propositional reasoning constitutes an integrated system of the combinatorial of the two propositions - thus producing 16 binary propositions (Table 1) - and a group of four transformations which transform the propositions into one another (Table 2).

Table 1 gives alternate representations of the 16 logical propositions which can be obtained from the set of four base elements, p.q, P.q, P.q and p.q (obtained from the initial two propositions) by considering them one-by-one, two-by-two, three-by-three, all four and including the null set.

As in the physical system, Piaget argued that the 16 binary propositions can be related to one another by the group of inversions and reciprocities - the INRC (Table 2).

Thus, if we let P stand for "he is hungry" and q for "he is tired", then their cancellations P and q represent "he is not hungry" and "he is not tired" respectively. Now, if we choose their conjunction, i.e. p.q as the identical operation, then the following four relations result.

I (P.q) = he is hungry and tired
N(P.q) = P v q = he is not hungry or he is not tired.
This statement is a strong denial of the original and hence its inversion.
R(P.q) = P.q = he is not hungry and he is not tired.
This statement is a weak denial of the original proposition and hence its reciprocal
The Combinatorial of the Propositional Elements of Piaget's Model of Formal Thought

<table>
<thead>
<tr>
<th>Verbal Label</th>
<th>Class Notation</th>
<th>Logic Notation</th>
<th>Piaget Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Complete Affirmation</td>
<td>$A_1A_2 + A_1^iA_2 + A_1^iA_2 + A_1^iA_2$</td>
<td>$(P.q)v(P.q)v(P.q)v(P.q)$</td>
<td>$P^q$</td>
</tr>
<tr>
<td>2. Complete Negation</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3. Conjunction</td>
<td>$A_1A_2$</td>
<td>$P.q$</td>
<td>$P.q$</td>
</tr>
<tr>
<td>4. Incompatibility</td>
<td>$A_1A_2 + A_1^iA_2 + A_1^iA_2$</td>
<td>$(P.q)v(P.q)v(P.q)$</td>
<td>$P/q$</td>
</tr>
<tr>
<td>5. Disjunction</td>
<td>$A_1A_2 + A_1^iA_2 + A_1^iA_2$</td>
<td>$(P.q)v(P.q)v(P.q)$</td>
<td>$Pvq$</td>
</tr>
<tr>
<td>6. Conjunctive Negation</td>
<td>$A_1A_2^i$</td>
<td>$\overline{P.q}$</td>
<td>$\overline{P.q}$</td>
</tr>
<tr>
<td>7. Implication</td>
<td>$A_1A_2 + A_1^iA_2 + A_1^iA_2$</td>
<td>$(P.q)v(P.q)v(P.q)$</td>
<td>$P\supset q$</td>
</tr>
<tr>
<td>8. Non-Implication</td>
<td>$A_1A_2^i$</td>
<td>$P.q$</td>
<td>$P.q$</td>
</tr>
<tr>
<td>9. Reciprocal Implication</td>
<td>$A_1A_2 + A_1A_2 + A_1A_2^i$</td>
<td>$(P.q)v(P.q)v(P.q)$</td>
<td>$q\supset P$</td>
</tr>
<tr>
<td>10. Negation of Reciprocal Implication</td>
<td>$A_1A_2^i$</td>
<td>$\overline{P.q}$</td>
<td>$\overline{P.q}$</td>
</tr>
<tr>
<td>11. Equivalence</td>
<td>$A_1A_2 + A_1^iA_2$</td>
<td>$(P.q)v(P.q)$</td>
<td>$P=q$; or $P \not\subseteq q$</td>
</tr>
<tr>
<td>12. Reciprocal Exclusion</td>
<td>$A_1A_2^i + A_1A_2^i$</td>
<td>$(P.q)v(P.q)$</td>
<td>$Pv vq$</td>
</tr>
<tr>
<td>13. Affirmation of P</td>
<td>$A_1A_2 + A_1A_2^i$</td>
<td>$(P.q)v(P.q)$</td>
<td>$P[q]$</td>
</tr>
<tr>
<td>14. Negation of P</td>
<td>$A_1A_2^i + A_1A_2^i$</td>
<td>$(P.q)v(P.q)$</td>
<td>$\overline{P}[q]$</td>
</tr>
<tr>
<td>15. Affirmation of q</td>
<td>$A_1A_2 + A_1A_2^i$</td>
<td>$(P.q)v(P.q)$</td>
<td>$q[P]$</td>
</tr>
<tr>
<td>16. Negation of q</td>
<td>$A_1A_2^i + A_1A_2^i$</td>
<td>$(P.q)v(P.q)$</td>
<td>$\overline{q}[P]$</td>
</tr>
</tbody>
</table>

* Key on next page.
KEY TO TABLE 1

VERBAL LABELS:

These are Piaget's labels. Some synonymous labels are:
Tautology = Complete Affirmation; Conditional = Implication;
Biconditional = Equivalence; "the inclusive or" = Disjunction;
"the exclusive or" = Reciprocal Exclusion.

CLASS NOTATION:

\( A_1 \) = occurrence of Class 1   \( A_1' \) = non-occurrence of Class 1
\( A_2 \) = occurrence of Class 2   \( A_2' \) = non-occurrence of Class 2

There are 4 possible pairs: \( A_1A_2, A_1A_2', A_1'A_2, A_1'A_2' \).

Each of these pairs in turn represents an element of a new category;
these pairs are the product of logical multiplication of classes.

LOGIC NOTATION:

\( P \) is the generalized abstraction corresponding to \( A_1 \);
assertion \( P \) is true

\( q \) is the generalized abstraction corresponding to \( A_2 \);
assertion \( q \) is true

\( \overline{P} \) is the generalized abstraction corresponding to \( A_1' \);
assertion \( P \) is false

\( \overline{q} \) is the generalized abstraction corresponding to \( A_2' \);
assertion \( q \) is false.

Combinations are represented by the logical conjunction \( \cdot \) and \( \lor \)

\( \cdot \) = and/both (e.g., \( P \cdot q \) = both \( P \) and \( q \) are true); it represents logical multiplication.

\( \lor \) = either or both and corresponds to + in Class Notation;
it stands for logical addition (e.g. \( P \lor q \) = either \( P \) or \( q \) or both are true).

Parentheses ( ), Bound or set off components.
### Table 2


<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
</table>
| **IDENTITY** | Application of the Identity Operator to a logical representation of a proposition yields an equivalent representation of the same proposition. Equivalence is determined by construction of truth tables according to the conventions of standard logic. Every proposition has a unique identifying truth table. | \[ I((P \land q) \lor (P \land \overline{q}) \lor (\overline{P} \land q)) = P \lor q \]
| | I(Disjunction) = Disjunction | |
| **CORRELATION** | The correlation Operator changes the conjunctions in the logical representation of a proposition by substituting "\(\lor\)" for "\(\land\)" and vice versa. | \[ C(P \land q) = P \lor q \]
| | C (Conjunction) = Disjunction | |
| **RECIPROCITY** | The Reciprocal Operator changes the signs in the logical representation of a proposition by addition of the negation symbol (\(-\)), where it is absent and its deletion where present. | \[ R(P \land q) = \overline{P} \lor \overline{q} \]
| | R (Conjunction) = Conjunctive Negation | |
| **NEGATION** | The Negation Operator changes both signs and conjunctions in the logical representation of a proposition: | \[ N(P \land q) = \overline{P} \lor \overline{q} \]
| | N (Conjunction) = Incompatibility | |
\[ C(P.q) = P \lor q = \text{he is hungry or tired} \]

This statement is nearer to the original than the others and hence may be called its correlative.

Thus, the four interpropositions, \( P.q, \bar{P} \lor \bar{q}, \bar{P}.\bar{q} \) and \( P \lor q \), form a group of four transformations isomorphic to the INRC group just as problems of reciprocity in physical systems form a similar group. That is, the propositional reciprocities and inversions express the reciprocities and inversions operating in the equilibrated system under study.

Inhelder and Piaget (1958) explained this psychological unity between propositional logic and reciprocity in physical systems by saying that the INRC group functions at two levels - initially,

"...it governs the propositional operations which the subject uses to describe and explain reality; as such it constitutes an integrated structure at the interior of his thought, ... (and then) as a result of this first function it is projected outside into the phenomena under study (since in the given data, these consist of a physical system whose equilibrium represents the very problem to be resolved)." (Inhelder and Piaget, 1958, p. 32)

According to Inhelder and Piaget, the INRC group is therefore not restricted to mechanical systems alone but is applicable in all situations involving the coordination of two distinct reference variables like concentration and solution volume in titration in chemistry.

The relationship of the INRC group to the proportional schema, i.e. to concepts involving both reciprocity and proportion, is expressed by Inhelder and Piaget as follows:
The possibility of reasoning in terms of a group structure - INRC - indicates our understanding of the equalities NR = IC, RC = IN, NC = IR, etc., the equalities between products of two transformations. The result is that the INRC group is itself equivalent to a system of logical proportions:

\[
\frac{Ix}{Cx} = \frac{Rx}{Nx} \quad \text{or} \quad \frac{Rx}{Ix} = \frac{Cx}{Nx}
\]

Since \( IN = RC \) (where \( x \) = the operation transformed by \( I, N, R, \) or \( C \)). (Inhelder and Piaget, 1958, p. 177).

That is, proportionality is a consequence of the discovery of logical reciprocity. Using the Equilibrium in the Balance Task, as an example, they argued that the above proportion corresponds to the numerical proportion:

\[
\frac{nx}{ny} = \frac{n: y}{n: x}
\]

where \( x \) and \( y \) correspond to the weight and distance from the fulcrum, respectively; and \( n \) = coefficient given to an increase in \( x \) or \( y \). Since in their view, the INRC group is fundamental to propositional logic, they argue that subjects from 12 years to 15 years discover proportionality because they can think in terms of propositional logic and therefore are able to understand and transform the equality of two products.

One of the experiments designed by Inhelder and Piaget (1958) to illustrate proportional reasoning is the Equilibrium in the Balance. This will be used to show the application of his analysis of this schema. This problem is chosen because it involves reciprocal proportion (i.e.
reciprocity and proportion) in contrast to the problem of the communicating vessels which involves only reciprocity; also, it is isomorphic to some of the calculations in volumetric analysis as will be shown later.

The balance task concerns the discovery and explanation of the relation between the weights placed on the balance and their distances from the fulcrum. That is,

\[ \frac{W}{W'} = \frac{L'}{L} \]

where \( W \) and \( W' \) are two unequal weights \( L \) and \( L' \) are their corresponding unequal distances,

The balance scale used is a simple seesaw type balance with varying weights which can be hung at different points along its two arms.

The successful solution of this problem is assumed to depend on two conceptual systems: the reciprocity that obtains between weight and distance and which according to Piaget is reflected in the propositional reasoning of the subject, and the notion of proportion itself as opposed to additive differences or seriation and correspondences. That is, instead of subtracting from the distance along the arm, \( L' \), whatever is added to the weight \( W \), or adding to \( L \) whatever is subtracted from \( W \), the successful application of the proportionality schema involves the abstraction of a second order relation from the elementary relations.

Thus given:
the discovery of proportion lies in the ability to abstract the second order relation:

\[ \frac{W}{W'} = \frac{L}{L'} \]

instead of relying on the additive differences,

\[ W-W' = L'-L. \]

In short, successful solution of the balance problem involves the use of true proportions or ratios. Piaget analyzes the proportionality involved in this task as follows:

If the increase in weight is represented by \( P \) its decrease or negation can be denoted by \( \bar{P} \). However, the increase in weight can be compensated by a corresponding decrease in distance from the fulcrum and this can be denoted by \( \bar{q} \) while the negation of this, \( q \), i.e. increasing the distance from the fulcrum, compensates for the decrease in weight. The following formulation then results:

\[ I(P); N(\bar{P}); R(\bar{q}); C(q) \]

This is equivalent to the proportionality:

\[ \frac{P}{\bar{q}} = \frac{q}{\bar{P}} \quad \text{thus} \quad \frac{Ix}{Rx} = \frac{Cx}{Nx} \quad \text{where} \ x = P \]

Also, \( \frac{P}{q} = R \frac{\bar{P}}{\bar{q}} \), and as such \( (P,q) = R(\bar{P},\bar{q}) \)
That is, understanding the system of inversions and reciprocities follows from an understanding of the above proportional relation. In other words, increasing the weight and reducing the distance on one arm of the balance is similar to reducing the weight and increasing the distance on the other arm. A similar analysis could be applied to a typical problem in volumetric analysis such as:

If 20 mL of 2M H₂SO₄ neutralizes 100 mL of NaOH solution, what will be the molarity of the NaOH solution?

Successful solution of this problem may involve the recognition of the two types of proportions - inverse proportion and direct proportion in the problem.

In the first case, as in the problem of Equilibrium in the Balance, the subject must be able to recognize the reciprocity that obtains between the concentration and the volume of the solutions and at the same time be able to use ratios and proportions instead of additive differences. That is, the first part of the problem is solved if the subject is able to identify the inverse proportionality that obtains between the concentration and the volume of the solutions.

The solution to the problem is finally completed by recognizing the direct proportion that obtains between the product of the concentration and volume of the solutions (i.e. the number of moles of the reactants) and the coefficient of the reactants (H₂SO₄ and NaOH) in the stoichiometric equation. Symbolically, it can be stated that:
\[ \frac{C_A}{C_B} = \frac{V_B}{V_A} \text{ or } C_A V_A = C_B V_B \text{ reciprocal proportion} \]

and,

\[ \frac{C_A V_A}{1} = \frac{C_B V_B}{2} \text{ or } \frac{C_A V_A}{C_B V_B} = 1/2 \text{ direct proportion} \]

where

- \( C_j \) stands for the concentration of acid or base
- \( V_j \) stands for the volume of acid or base
- 1 and 2 stand for the coefficient in the stoichiometric equation.

Considering the relation between volume and concentration, if the increase in concentration is set forth as the identical operator and represented by \( P \), then its decrease or negation is the inverse transformation \( \bar{P} \). But the decrease in the volume of the solution compensates for the increase in concentration without cancelling it. Hence it plays the part of reciprocal transformation, \( \bar{q} \). The inverse of the reciprocal produces a similar effect as the decrease in concentration and can be regarded as playing the role of the correlate, \( q \). Thus, the following transformations:

\[ I(P); N(\bar{P}); R(\bar{q}); C(q) \text{ result.} \]

This yields the following proportion,

\[ \frac{P}{q} = \frac{\bar{P}}{\bar{q}} \text{ or } (P \cdot \bar{q}) = R (\bar{P} \cdot q) \]
Considering the relation between the coefficient in the balanced equation and number of moles of reactants used in the titration, the following situation exists:

If an increase in the stoichiometric coefficient is denoted as the identical operator, $P$, then its decrease is the inverse operation, $\bar{P}$. The decrease in the number of moles of reactants compensates for the decrease in stoichiometric coefficient, thus acting as the reciprocal transformation, $q$. The inverse of the reciprocal, $q$, i.e. increase in the number of moles, produces an effect similar to the increase in the stoichiometric coefficient and is thus its correlative.

The proportional relation resulting from the above transformation is:

\[
\frac{P}{q} = \frac{\bar{q}}{\bar{P}} \quad \text{or} \quad \frac{I_x}{C_x} = \frac{R_x}{N_x}
\]

In other words, the increase of stoichiometric coefficient is to the increase of number of moles as the decrease of number of moles is to the decrease of stoichiometric coefficient.

It should be noted that the above relation requires knowledge or ability to write and interpret a balanced equation of the reaction between the reactants, viz.,

\[
H_2SO_4 + 2 \text{NaOH} = Na_2SO_4 + 2H_2O
\]

That is, knowledge of content may play an important part in obtaining a successful solution to the problem. Piaget (1972) has acknowledged that the content in a particular area may help
a subject to use formal reasoning which includes proportional reasoning in situations requiring it.

It has been argued that Gagné's cumulative learning theory offers the opportunity to examine the influence of the content in learning or problem solving (Griffith, 1979).

The next section will therefore briefly summarize Gagné's theory and attempt to identify differences between Gagné's theory and Piaget's theory.

Gagné's Theory of Learning

In contrast to Piaget, Gagné views development as subordinate to learning. According to him, learning is a cumulative process involving the transfer of certain intellectual skills such as discriminations, concepts and rules to a variety of problem solving situations and in learning a number of higher-order skills. As such, development is seen as the long term effect of learning.

From this belief in the cumulative effect of learning, Gagné argues that individuals acquire capabilities in an ordered and additive manner. That is, the learning of a more complex skill is preceded by the learning of less complex one which is also preceded by a much less complex skill and so on, until the most basic component of the skill is encountered.

Gagné (1970, p. 20) distinguishes himself from the traditional position that all learning can be accounted for by any particular prototype of learning such as association or insight, by believing that there might be as many different
types of learning as there are conditions under which learning can occur. He distinguishes eight different types of learning which in his view form a hierarchical structure in which the subordinate types are prerequisite to the learning of the superordinate ones. The developmental nature of this cumulative model is represented in Figure 2 (Gagné, 1970, p. 70). According to Gagné, the hierarchy can be generated by asking the question "What must the student first be able to do if he is to achieve a particular capability?" This is repeated for any new capability generated until simple and less demanding capabilities are arrived at. Applied to the Ideal Gas Law, the complex superordinate rule to be learned can be mathematically expressed as follows:

\[ PV = nRT \]

where \( P \) = pressure, \( V \) = volume, \( n \) = moles, \( R \) = universal gas constant, and \( T \) = temperature. It may be hypothesized that this complex rule requires the learning of rules governing temperature and volume (i.e. Charles Law) and pressure and volume when temperature is held constant (i.e. Boyle's Law). The learning of these two rules can be further hypothesized to require the following concepts as prerequisites - temperature, volume, pressure, mass and mole.

It is noteworthy that Gagné has changed his theoretical stance to some extent since the publication of his book, *Conditions of Learning* (Gagné, 1970). In his earlier writings Gagné (1970) believed that the hierarchical structure could be applied to any content area. He stated, "learning hierarchies are the best way to describe the structure of any
Problem Solving (Type 8)

which requires as prerequisites:

Rules (Type 7)

which requires as prerequisites:

Concepts (Type 6)

which requires as prerequisites:

Discriminations (Type 5)

which requires as prerequisites:

Verbal Associations (Type 4)

or chains (Type 3)

which require as prerequisites:

Stimulus-Response Connections (Type 2)

Signal Learning (Type 1)

Figure 2

Hierarchical Arrangement of Learning Types
(Gagné, 1970, p.66)
topic, course, or discipline" (Gagne', 1970, p. 245). However, in his more recent works he has moved from this position by suggesting that the hierarchical structure can be applied only to certain kinds of learning (Gagne', 1972; 1977; Gagne' and Briggs, 1974). In these recent writings, he distinguishes five domains of learning which he calls motor skills, verbal information, intellectual skills, cognitive strategies, and attitudes. Gagne (1972) suggests that of the five domains, it is only the intellectual skills learning which require prior learning of subordinate prerequisite skills. That is, the hierarchical model can be applied only to the intellectual skills. The intellectual skills domain consists of the eight types of learning originally postulated by Gagne' (1970) and shown in Figure 2.

Although learning in any particular domain may be affected in some way by learning in the other domains, only the learning of intellectual skills and its relation to cognitive strategies will be considered. This is because it is the only domain which has been analyzed in detail in Gagne's theory and also the domain which related to the content of a task; thus making it applicable to the proposed study.

Gagne makes a distinction between intellectual skills and cognitive strategies in the following way. Whereas the application of rules or concepts in a meaningful way in any subject area represents intellectual skills; the way an individual attacks a novel problem constitutes his cognitive strategy (Gagne' and Briggs, 1974, p. 49). Gagne' and Briggs
(1974) consider cognitive strategy as an internally organized skill. They relate it to intellectual skills by referring to cognitive strategy as a very special kind of intellectual skill in that it develops out of "specially learned intellectual skills by a process of generalization" (Gagné and Briggs, 1974, p. 48) and are therefore important in novel or problem solving situations. They suggest that a major difference between cognitive strategies and intellectual skills is the object of the skill. Whereas intellectual skills are oriented toward the objects in the individual's environment such as graphs, formulas, and statement of laws, cognitive strategies have as their objects the individual's own thought processes such as how critically he thinks and how fluently he thinks. That is, intellectual skills are subject matter oriented whereas cognitive strategies pertain more to the behaviour of the individual, regardless of what he is studying or the problem he is solving, and are as such 'content free'.

Although Gagné suggests that cognitive strategies are of particular importance in problem solving, he maintains that if an individual is to arrive at a specific solution to a particular problem, the intellectual skills or more specifically, the concepts and rules required for its solution must be available to the learner.

In the next section, a comparison of the two theories, namely Gagné's theory and Piaget's theory and their possible combination from a theoretical viewpoint will be considered.
Comparison of Gagné's and Piaget's Theories

It is interesting that Gagné (Gagné and Briggs, 1974, p. 48) attempts to relate the domain of cognitive strategies in his theory to the intellectual structure of the individual as posited by Piaget. This is important given the attempt in the present study to examine students performance on a chemical problem in terms of both the proportional reasoning schema in Piaget's theory and the content requirements as identified using Gagné's theory.

According to Piaget (1964), the individual's intellectual structure sets the limits to the kinds of problem solving an individual can successfully perform while at the same time accommodating to the environmental stimulus. In contrast, the Gagnéan theory suggests that the subordinate prerequisite capabilities set the limits for what can be learned. Thus Gagné (1970, p. 290) argues that "differences in developmental readiness are primarily attributable to differences in the number and kind of previously learned intellectual skills".

Strauss (1972) suggests that on the surface, the two theories appear to agree on the following: (1) that an individual develops an increasing number of intellectual capabilities as he grows older, (2) that such capabilities are the product of an individual's interaction with his environment, and (3) that the acquisition of these capabilities is sequential. He, however, notes that these apparent generalizations are misleading since the two theories entertain entirely different philosophical positions.
Strauss suggested that although both Piaget and Gagné view intellectual capabilities as forms of thought which can be applied to different contents, there are theoretical differences in the nature of the forms. He argues that in Gagné's theory the forms of thought are narrowly defined structures such as the specific responses, discriminations, concepts, rules and problem solving which constitute a hierarchy; in the Piagetian theory, they are potential organizations of mental structures and are therefore much more comprehensive.

A second difference identified by Strauss is that in the Gagnéan theory, the learner copies reality rather than constructs reality. Hence the learner is a relatively passive recipient of the environmental stimuli, while in Piaget's theory, the learner is very active in constructing his intellectual structures. This interpretation of Gagné's theory may be justifiable only to the intellectual skills since Gagné claims that it is in this domain that learning can be carefully controlled to aid the acquisition of higher-order skills. As Griffiths (1979) suggests, the difference between Piaget and Gagné is more likely to centre around the extent to which the learner is controlled. An important aspect of this control is whether the majority of individuals need to follow a single hierarchic organization of a particular concept as Gagné's theory suggest, or whether a variety of potential routes should be available as Piaget's theory suggests. Rowell and Dawson (1979) suggests that
Gagné does not consider a 'multi-path' to development because he approaches learning principally from the viewpoint of instruction rather than a consideration of natural or 'unforced' development. Some evidence suggests that a single hierarchy of subskills is unlikely to characterize the development of any particular concept since children of different ages use different methods and different processes, or the same processes in different orders, in reaching a developmental goal (Schaeffer, Eggleston and Scott, 1974).

The differences in the theoretical positions as noted by Strauss (1972) and Rowell and Dawson (1979) need not preclude the application of both theories in situations in which their use may be advantageous. In fact, these differences when combined may help in better understanding a subject's performance on a task. As noted by Lovell (1971a), Piaget's theory does not say much about the content of a task, a situation which can be contrasted with his detailed analysis of the intellectual structures needed for its solution. On the other hand, Gagné's theory gives a detailed hierarchical description of the content of the problem.

The combination of the two theories may remove some of the problems encountered when either theory is employed alone in research. This need is exemplified by White's finding which indicated the "subject's failure to learn even when he possesses all the apparently necessary subordinate elements" (White, 1972). The examination of the intellectual reasoning of the subject may explain this finding. On the
other hand Sticht (1971) suggests that the problem of horizontal decalage in Piagetian research may be removed by providing the appropriate prerequisite content.

Thus it can be seen that the combination of the two theories may be fruitful in affording a better explanation of students' difficulties with certain tasks in the school curriculum.

The next section will be concerned with the discussion of studies related to proportional reasoning structures and the content of science tasks, especially those concerned with chemical problems.

Related Study: Proportional Reasoning and Content

The following section will attempt to show that Piaget's theory and Gagné's cumulative theory have been used independently in analysing a subject's performance on a task. A possible combination of both theories in a single study is suggested after reviewing studies which demonstrate the influence of content on logical reasoning as proposed in Piaget's theory.

Proportional Reasoning Studies

The importance of studying the proportional reasoning of students cannot be underestimated since it forms a vital aspect of the understanding of quantitative relations in science and also because it forms an essential part of Piaget's formal operations.
During the last two decades, a substantial portion of the science education literature has been geared to applying Piaget's theory to science curriculum and instruction (e.g. Karplus, 1965). A fair proportion of this literature has been concerned with the proportional reasoning of students in both the elementary and high schools (e.g. Karplus and Peterson, 1970; Chiappetta, 1974). It should be mentioned that a number of studies have not dealt with proportional reasoning per se but only as part of the total abilities which characterizes formal operations. Examples of such studies include those by Lovell (1961) and Lawson and Renner (1975) where tasks requiring proportional reasoning were used with tasks requiring control of variables or other schema in deciding on the cognitive developmental level of the subject. Since the aim of such studies was not to identify proportional reasoning or its relation to some other construct per se, these studies will not be discussed here. The studies discussed here deal specifically with proportional reasoning. The order of presentation include references to the analysis of chemical concepts in terms of Piaget's theory, and the presence of proportional reasoning in adolescents.

Proportional Reasoning as an Explanatory Construct

From Piaget's theory it appears that the intellectual structure of the subject should dictate his performance on a task requiring this structure. To this end a number of studies have appeared in the literature which attempt to explain students difficulties in terms of the intellectual
structure. Mealings (1963) and a number of researchers (Ingle and Shayer, 1971; Shayer, 1972; Herron, 1975; Harford and Good, 1976; Karplus, 1977; Chappeta 1978) have analyzed concepts in school science curricular materials solely in terms of their underlying intellectual structure. Mealings (1963) conducted a study in which he investigated the reasoning used by students in solving certain science problems. From the results, he suggested that students under 16 years of age will find it difficult to undertake topics requiring an understanding of metric proportion such as valency, equivalency and Boyle's Law. He also suggested that under 14 years of age, a student will not be able to distinguish between potassium sulphate, potassium carbonate, magnesium sulphate and magnesium carbonate by means of practical tests.

From this lead, Ingle and Shayer (1971) analyzed the intellectual demands of the topics in the Nuffield 'O' Level chemistry course in terms of Piaget's stages. According to their analyses, most secondary school students will encounter difficulties with topics such as the mole concept and its associated calculations since proportions and ratios are involved. In a similar analysis related to the topics in the Nuffield 'O' Level physics course, it was concluded that topics such as kinetic theory and energy will present a constant source of difficulty for students (Shayer, 1972).

Hartford and Good (1976) analyzed the conceptual demands of certain topics in the CHEM Study texts in terms of Piaget's formal operation theory and noted that chemical bond-
ing and equilibrium require a high level of cognitive development. Herron (1975) presented a list of 16 commonly expected competencies which chemistry students who are concrete operational could be expected to exhibit. Each of these competencies were compared with the intellectual demands judged to be required by the science curriculum. He argued that a number of areas required formal operational abilities to successfully understand the concepts and problems involved. For example, given the volume of base needed to neutralize 1.0 g of acid, a concrete operational student can calculate the volume of base needed to neutralize any amount of acid. However, according to Herron, the same student cannot calculate the concentration of an acid if he is given the concentration and volume of base needed to neutralize a certain volume of the acid. Herron's analysis suggests that students difficulties in volumetric analysis calculations is attributable to lack of understanding of the inverse proportionalities involved.

Karplus (1977) has also suggested that certain concepts such as chemical bonding, periodic system and ideal gas which are usually included in secondary school science courses may be more difficult for students in that they demand formal reasoning. There is much recent evidence that suggests that as many as 50% of some samples of high school and college students have failed to acquire a working understanding of the proportionality schema (e.g. Karplus and Peterson, 1970; Lunzer and Pumfrey, 1966; Lovell, 1961; Lunzer, 1965; Wollman and Karplus, 1974). In Karplus
and Peterson's (1970) study a Paper Clips Task (which measures direct proportion) was administered to students from Grade 4 to 12. Their finding indicated that a large proportion of high school students use additive strategies in situations requiring the use of proportion. A similar conclusion was arrived at by Lovell and Butterworth (1966). A study by Chiappetta (1974) using adults as subjects showed that about 50% of the adults used additive strategies on a solubility problem which required direct proportion. Chiappetta (1976) arrived at a similar conclusion after reviewing Piagetian studies related to high school and college science education.

This apparent lack of congruence between the curriculum materials used in the schools and the intellectual development of high school students leads to the question of whether an empirical relationship exists between the intellectual reasoning of students and their achievement. Griffiths (1979) reviewed studies relating cognitive developmental level to science achievement and suggested that such evidence is scarce. Of particular interest to the present study and even more scarce is the evidence needed to answer the question: is there an empirical relationship between proportional reasoning of high school students and their achievement in science? The only studies reported on this question are those conducted by Chiappetta (1974) and Wheeler and Kass (1977).

Chiapetta (1974) investigated the relationship between female in-service teachers' ability to reason in terms
of proportion and their achievement in physical science. The subjects were first given the Equilibrium in the Balance task to assess their proportional thought development. They then participated in a self-paced 12-unit physical science laboratory course. One of the units was chemical solubility whose objectives were concerned with calculations involving proportions and ratios. The physical science achievement of the subjects was assessed at two points using a paper and pencil test followed by an interview. One achievement test was given at the completion of the unit on solubility and the other at the end of the course. A correlation of 0.60 was found between performance on the Equilibrium in the Balance Task and achievement in solubility while a correlation of 0.80 was found between the Equilibrium in the Balance Task and achievement on all the physical science laboratory units. Chiappetta concluded that the proportional reasoning of the subjects appeared to be directly related to their physical science achievement. However, no attempt was made to relate their achievement to their understanding of the content area. Only the logical structure was considered as relevant in explaining achievement.

Wheeler and Kass (1977) studied the relationship of the proportional reasoning schema to achievement in four areas of chemistry - chemical nomenclature and writing of formulae, chemical reactions, the mole concept and gravimetric stoichiometry. The subjects involved were 168 high school chemistry students. The subjects were initially administered three
proportional reasoning tasks and a general proportional reasoning test. The tasks used were Equilibrium in the Balance, the Ratio Task which is a modification of the Paper Clips Task (Wollman and Karplus, 1974) and the Metric Puzzle which involved conversion from inches to centimeters. They also employed the Island Puzzle (Karplus and Karplus, 1970) which was employed to assess deductive reasoning. At the conclusion of each of the four introductory chemistry units which were taught by the regular teachers, a subtest measuring content in that unit was administered. At the end of the course a chemistry achievement test which had items similar to the items in the chemistry subtests were administered. The similarity of the chemistry achievement test and the subtests is shown by a high positive correlation coefficient of 0.79. The authors reported a significant relationship between the students' ability to apply proportional reasoning and achievement in chemistry. However, in this case the authors also examined the effect of content but this is discussed in the next two sections. Even though the tasks on proportional reasoning included both inverse and direct proportionality tasks, no attempt was made to examine how these two aspects of proportionality separately and interactively affect subjects achievement in chemistry.

Thus with the exception of the study by Wheeler and Kass, the above studies have mainly examined the structural demands of chemical concepts in curricular materials or have examined only the influence of proportional reasoning on
achievement. Generally, the content has not been considered as a relevant variable in the studies.

**Content as Explanatory Construct**

Apart from the use of subject's proportional reasoning in the above studies to explain their difficulties, other studies have focused on the content of the tasks in explaining these same difficulties.

Duncan and Johnstone (1973) conducted a study in an attempt to identify the difficulties encountered by high school students in understanding the mole concept and some of its applications - solution concentration and volumetric work. A paper and pencil multiple choice test was used. They found that the students' difficulties were related to their understanding of the concepts subsumed by the mole. Specifically, they reported that the difficulties seem to relate to (i) overcoming the misapprehension that one mole of a compound will always react with one mole of another, regardless of the stoichiometry of the reaction, (ii) balancing equations, and (iii) manipulation of molarity of solutions. A study by Kass (1977) on the mole concept reported difficulties students have in correctly balancing equations prior to their use in stoichiometric calculations. Novick and Menis (1976) conducted a study of high school students' perception of the mole concept using a structured interview procedure. They discovered that the students' difficulties involved (i) thinking of the mole in terms of mass and not in terms of number; this, they believed
originates from quantitative operations based on mass measurements, (ii) restricting the mole concept to a certain number of particles of gas, and (iii) thinking of the mole as a property of a molecule.

The above studies demonstrate the importance of prerequisite content in chemistry achievement. To anticipate students' difficulties in terms of the subsumed prerequisite concepts demanded by a particular task, a content analysis can be performed on the task. Gagné's hierarchical theory provides such a means for getting at the subsumed concepts. A number of studies have analyzed certain chemical concepts using this approach. Gower, Daniels and Lloyd (1977b) analyzed the mole concept using Gagné-type of hierarchical analysis and found that it subsumes other lower level concepts which students have to master before understanding the mole. Their study involved the written responses of 24 high school students to a set of written items representing the elements of the hypothesized hierarchy. They found that the connections established corresponded closely to those predicted in the hypothesized hierarchy. However, the authors noted that the small number of subjects involved in the study precludes generalization of the findings. In another work, Gower, Daniels and Lloyd, (1977a), analyzed volumetric analysis calculations using Gagné's theory and found it to subsume a number of important lower-order concepts (Figure 3).

A similar line of approach was followed by Griffiths and Kass (1979) in their attempt to identify a hierarchy
Hierarchical Analysis of Titration Calculations
(Gower, Daniels and Lloyd, 1977a)
representing the mole. Using a large sample of high school chemistry students, they were able to obtain a relationship between the empirical connections and the hypothesized one. That is, achievement in the mole concept was found to be dependent on the subsumed concepts. A similar result was obtained by Okey and Gagne (1970) in a study in which they used solubility product problems as the concept of interest.

A general conclusion from the above studies is that the subsumed concepts may be critical to a subject's performance on a task. However, again only one variable, the content was used in explaining the performance of the subjects. The structural component of the tasks was not considered.

Influence of Content on Logical Reasoning

The above discussions dealt with studies which employed either proportional reasoning or content in explaining students' difficulties. The studies to be discussed below demonstrate the probable influence of the nature of the content on logical reasoning and hence demonstrates the need to examine both in order to achieve a better understanding of students' difficulties.

A number of studies have shown that the content of a task may have a significant effect on the recognition of underlying logical structure of the task. A classic example of this was demonstrated by Wilkins (1928) in her attempt to find the effect of familiar everyday content, unfamiliar content and symbolic content on the solution of syllogisms.
She discovered that her subjects found the problems with familiar content easier to handle than problems with symbolic or unfamiliar content. In a similar study conducted by Roberge and Paulus (1971) a substantial and highly significant content effect was found.

Another clear demonstration of the effect of content is given by a series of studies based on Wason's (1966) Four Card Problem (e.g. Johnson-Laird, Legrenzi and Legrenzi, 1972; Wason and Shapiro, 1971; Lunzer, Harrison and Davey, 1972).

Although only deductive reasoning was considered in the above studies, one implication is that the content of a task may be more important than the proportional reasoning underlying it. Another implication is that the content and proportional reasoning may interact to affect a subject's performance on a task. There exist the need therefore, for studies which examine the relationship among content, proportional reasoning and achievement.

The importance of the content in problem solving situations has been reiterated by a number of writers (Levine and Linn, 1977; Lovell, 1971a; 1973; Lunzer, 1965; Nagy and Griffiths, 1979). Levine and Linn (1977) in a review of research on adolescent reasoning noted the need for research directed to the content of school subjects, the logical structure and students previous experience with the variables in the study in explaining their performance. Other researchers (Keating, 1979; Lovell, 1971a; 1973; Lunzer, 1965; 1975) have made similar suggestions. It is noteworthy that in
his more recent writings Piaget (1972) has come to acknowledge this position.

The recognition of the need to consider not only the structure but also the content of a task in identifying a student's difficulty is relevant to the present study. The study conducted by Wheeler and Kass (1977) and discussed earlier seems to fall in this domain. The authors considered the proportional reasoning structures and the content of certain introductory chemistry concepts on the performance of high school students on a chemistry achievement test. Their analysis showed that both content and proportional reasoning were significantly related to achievement. However, content accounted for a higher percentage (63.4%) of the total variance of the chemistry achievement test scores. Further, a stepwise regression analysis for the prediction of chemistry achievement also revealed that the proportional reasoning tasks did not add significantly to the regression equation once the scores from the chemistry content subtests had been entered. A similar finding was reported by Griffiths (1979) when developmental level scores were entered into a regression equation in which concepts subsumed by the mole had first been entered. These studies considered only the influence of structure and content on achievement but did not examine the interrelationships among them. To examine the relationships among all the relevant variables one approach is to develop a model of performance in which all the theoretical relationships among the variables are specified. Such a model is developed in the next section.
Path-Analytic Model of Performance

So far individual studies have been cited to justify the need to study the effect of content and proportional reasoning on achievement in chemistry. In the present section, results of studies reported in the literature and the theoretical assumptions of the structural theory of Piaget and the cumulative learning theory of Gagné will be used to construct a causal model involving the four variables - direct proportion, inverse proportion, subsumed prerequisite concepts and volumetric analysis calculations.

Studies conducted by Piaget and his associates indicate that problems of direct proportionality as in the experiments on the notion of similar triangles (Piaget, 1957) tend to be solved during early adolescence (i.e. around ages 11 and 12) while problems of inverse proportionality such as the Equilibrium in the Balance Task (Inhelder and Piaget, 1958) are solved at a later age (Lovell, 1971b). That is, there is a temporal order of development between direct proportion and inverse proportion. Stronger evidence for this was given by Rogers (1977) in an experimental study aimed at testing for a developmental sequence of acquisition of proportional reasoning in 16 year old high school physics students. The Paper Clips Task (Wollman and Karplus, 1974) (a first-order direct proportionality task), the Equilibrium in the Balance Task (a first-order inverse proportionality task), and two other tasks measuring second-order direct and second-order indirect proportionality were used in the study. Using an
ordering-theoretic approach, Rogers found that a prerequisite sequence exist between the first order direct proportionality and the first order inverse proportionality. A study by Lunzer and Pumfrey (1966) gives further support to the above findings that acquisition of direct proportionality precedes that of inverse proportionality.

The connection between direct proportionality and the subsumed prerequisite concepts (or content) is indicated by the work of Ingle and Shayer (1971), Herron (1975), Wheeler and Kass (1977), and Chiappetta (1979). Both Ingle and Shayer (1971) and Herron (1975) provided a theoretical analyses of the mole concept, stoichiometry, and other chemical concepts. Their analyses, based on Piaget's theory, indicated that the mole, stoichiometry, gram/mole conversions, and interpretation of equations require direct proportionality for understanding. Chiappetta (1979) has also indicated that stoichiometric calculation problems require (direct) proportional reasoning before an adequate understanding can be achieved. The study conducted by Wheeler and Kass (1977) and already discussed, showed a significant relationship between proportional reasoning and achievement in a criterion test testing the mole, gravimetric stoichiometry and chemical reactions which require direct proportion (Ingle and Shayer, 1971). The proportional reasoning in the study was measured using both direct and inverse proportionality tasks. But as the final concepts tested involved only direct proportion one could conclude that direct proportionality was necessary for achievement in the final test.
By logical extension of the preceding discussion, a relationship between direct proportionality and volumetric analysis calculations can be established. The application of Piaget's theory suggests that direct and inverse proportionality constitute the formal structures underlying volumetric analysis calculations (Herron, 1975; Wheeler and Kass, 1977). The assumptions involved in the theory suggests that the solution to such a problem (i.e. volumetric analysis calculation) will require the prior presence of direct and inverse proportional reasoning. Indirect evidence in favour of the connection between inverse proportionality and volumetric analysis calculations is provided in the study by Chiappetta (1974) that looked at the inverse proportional reasoning of subjects (measured using the Equilibrium in the Balance Task) and performance on a chemical solubility test. A moderate correlation (0.60) was found which may indicate the dependence of achievement in chemical concepts on inverse proportionality.

One of the subsumed prerequisite concepts in the present study is the calculations involved in the dilution of concentrated solutions. Analysis of such problems using Piaget's theory suggests that inverse proportionality underlies such problems (Herron, 1975). The implication is that solutions to these problems depend on the understanding of inverse proportionality.

No empirical study was found in the literature to show the influence of subsumed prerequisite concepts on volumetric analysis calculations per se. However, a number
of studies have reported on the influence of subsumed concepts on other chemical concepts. The study by Griffiths (1979) on the effect of concepts subsumed by the mole concept showed that the subsumed content were required for optimum performance on the problems related to the mole. The subsumed prerequisite concepts in the study were generated by using Gagné's hierarchical theory. A similar study conducted by Gower, Daniels and Lloyd (1977b) gave identical results. Okey and Gagné (1970) conducted a study in which the criterion variable was solubility product calculations. Using the hierarchical theory postulated by Gagné, they found that the difficulties encountered by the high school chemistry subjects used in the study were due to lack of the subsumed prerequisite concepts hypothesized in the study. The results of other studies (Duncan and Johnstone, 1971; Novick and Menis, 1976; Kass, 1977) indicate that success in a chemical task depends on the prior mastery of prerequisite concepts. From these studies, it can be hypothesized that knowledge of subsumed prerequisite concepts is necessary although not sufficient for successful performance on volumetric analysis calculations. Also the basic assumption of the Gagnéan theory that the learning of a higher order concept (e.g. volumetric analysis) depends on the learning of the lower order concepts subsumed by it, lends support to this hypothesis.

A diagrammatic representation of the integrated model as postulated above is given in Figure 4. This model will be referred to as the proposed integrated model. The omission
Figure 4: Proposed Integrated Model of Performance on Volumetric Analysis Calculations
of the linkage between direct proportional reasoning and performance on volumetric analysis calculations in the integrated model is essentially a theoretical assertion; since it is subsumed by all the other variables in the integrated model, these variables should mediate the influence of direct proportional reasoning on volumetric analysis calculations. As shown in this recursive model, direct proportionality is an exogeneous variable (i.e. it is not influenced by other variables in the model) while inverse proportionality, subsumed concepts and volumetric analysis calculations are endogeneous variables. Since it is never possible to account for the total variance of a variable, residual variables $R_4$, $R_3$ and $R_2$ are introduced into the integrated model to indicate the effect of variables not included in the integrated model such as prior experience of subjects.

The figure uses a standard convention in the methodological literature of representing observed or measured variables by squares. Also by convention since a recursive model is proposed, paths in the form of unidirectional arrows are drawn to indicate the direction of the causal influence with the causal flow originating in the variables taken as "causes" or explanatory and yielding the variables taken as effects (Kerlinger and Pedhazur, 1973, P.308). The use of the word "cause" in path analysis is only colloquial; it "is meant to provide no philosophical meaning beyond a shorthand designation for a hypothesized unobserved process" (Bentler, 1980). Thus other words like explanatory or process could be used for the same end.
Studies Related to the Secondary Questions in this Study

Questions posed in the secondary part of the study relate to the identification of specific student difficulties. For convenience, these difficulties can be grouped into those which relate to a misunderstanding of chemical concepts (i.e. conceptual difficulties) and those related to the place of laboratory work. Studies will be reviewed which relate to these broad areas.

A number of studies have been reported in the literature which examined the conceptual difficulties that students have on chemical concepts. These studies can be grouped into those which assess the conceptual difficulties of the students from their written work and those which employ clinical interviews.

The former include the studies by Duncan and Johnstone (1973), Doran (1972), Wheeler and Kass (1978), Johnstone, MacDonald and Webb (1977) and Rowell and Dawson (1980). The study by Duncan and Johnstone (1972) which was reviewed earlier employed multiple choice techniques to assess secondary school students' difficulties with concepts including the mole, stoichiometry and volumetric analysis calculations. The studies by Johnstone, MacDonald and Webb (1977) and Wheeler and Kass (1978) also examined the difficulties of secondary school students on chemical equilibrium problems using multiple choice tests. Doran (1972) also applied a multiple response format to identify the misconceptions of his subjects on the particulate nature of matter.
The above studies have therefore assessed the conceptual difficulties of subjects by developing item distractors according to predetermined misconception categories. As was noted by Wheeler and Kass (1978), the interpretation of the responses to such multiple-choice-type diagnostic tests presents certain problems in that a subject may obtain a correct answer by guessing or by arguing incorrectly. The subject can also obtain a particular incorrect response through a variety of different path ways. Thus, the use of multiple-choice tests to identify the conceptual errors of students may not reveal much about the subjects' difficulties. Studies are, therefore, needed which examine the conceptual difficulties of students using other approaches. The study by Rowell and Dawson (1980) falls in this domain. These authors identified the conceptual difficulties that secondary school students have with stoichiometry problems involving the mole by examining the written work of the students. They did not employ multiple-choice items. The students were given the question and were required to show their calculations. The steps used by the students in their written calculations were examined to identify the errors made by them. The approach used by Rowell and Dawson allowed them to identify, the conceptual errors made by the students. This approach should be applied to other chemical problems such as volumetric analysis calculations since Rowell and Dawson (1980) used it only for stoichiometric problems which are prerequisite to volumetric analysis calculations.
The studies which employed clinical interviews to assess the conceptual difficulties of subjects in chemistry are examplified by the studies done by Novick and his colleagues (Novick and Menis, 1976; Novick and Nussbaum, 1978). Clinical interviews have also been used to identify the conceptions of children about phenomena in other fields (e.g. Erickson, 1975; Anderson, 1965; Kargbo, Hobbs and Erickson, 1980).

The study by Novick and Menis (1976) which was previously discussed employed structured interviews to identify the conceptual difficulties that the secondary school subjects in the study had with the mole concept. A similar procedure was used by Novick and Nussbaum (1978) to examine the difficulties that secondary students had in understanding the particulate nature of matter. The authors noted that this approach was useful, in revealing the conceptual difficulties of the subjects since it allowed the probing of the initial responses of the subjects. Although, Sullivan (1967) has emphasized the need for the application of the clinical interview to investigate specific science concepts, the paucity of research studies utilizing chemical concepts in interview situations is notable. The need, therefore, exists for studies which employ this approach to investigate the conceptual difficulties with chemical concept such as volumetric analysis.

The above studies by Novick and his colleagues employing a question-and-answer technique during the clinical
interview can be differentiated from clinical interviews which employ the 'talking aloud' or "concurrent verbalization" (Ericsson and Simon, 1980) technique. However, according to Ericsson and Simon (1980) both techniques can produce reliable information about a subject's cognitive processes. They also stated that the demand for thinking aloud did not affect the processing abilities of subjects.

The talking aloud techniques has been used successfully to identify the strategies or cognitive processes of subjects on certain mathematical problems (e.g. Paige and Simon, 1966; Newell and Simon, 1972; Flaherty, 1974). More recently, Gorodetsky and Hoz (1980) applied it to certain science problems. However, the authors were more interested in the type and frequency of concepts used by their subjects. They were not interested in the strategies used by the subjects to arrive at solutions. However, their results indicate that this approach could be used to assess the strategies used by students when solving volumetric analysis problems.

Studies investigating students' difficulties with volumetric analysis laboratory work and the use of the laboratory work to assist students in overcoming their conceptual difficulties in volumetric analysis are similarly lacking. Infact, a review of the literature by Doran (1978) indicates that studies examining the laboratory techniques of chemistry students in general are lacking. The only studies reported in the literature which dealt with the laboratory skills of chemistry subjects were those by Eglen and Kempa (1974) and
Johnstone and McCallum (1972; cited in Johnstone and Sharp, 1979). The study by Eglen and Kempa (1974) sought to examine the degree of concordance among teachers' judgments of a student's manipulative laboratory skills, as presented on a video-tape. Different assessment techniques such as checklists and open-ended schedules were used by the teachers to compare the relative effectiveness of each of these techniques. This study did not seek to assess or investigate the laboratory skills per se of the students. However, studies have been conducted in other science areas to assess the acquisition of laboratory techniques (e.g. Kruglak, 1954; Tamir and Glassman, 1970). In some of these studies (e.g. Tyler, 1942) checklists were used to assess the skills of the students while in others (e.g. Kruglak, 1954) laboratory practical examinations were employed in a group situation.

The results of these studies indicate that while certain laboratory skills are learned quite well, others are poorly learned (Johnstone and Sharp, 1979; Johnstone and Wham, 1979; Doran, 1978). Johnstone and Wham (1979) attribute this to the insufficient emphasis on the mastery of skills. Doran (1978) suggests that this might be due to the emphasis each teacher gives to students' equipment manipulation and laboratory techniques.

Although the above result may be generalized to include chemistry students, the paucity of studies dealing with laboratory skills in chemistry suggest the need for studies which attempt to assess laboratory skills such as those found in titration.
Lacking in the literature are studies related to the use of laboratory work to reinforce theoretical knowledge. However, since this is regarded by chemistry teachers as an important objective for laboratory work it seems important for studies to be conducted to assess the claim.

In the next chapter, the data collection instruments and the pilot study will be discussed.
CHAPTER III

PILOT TESTING OF INSTRUMENTS AND PROCEDURES

Introduction

The previous two chapters dealt with the specification of the questions posed in this study and the rationale drawn from the literature to support the study of these questions. In this chapter, the instruments and the pilot study are discussed. The instrumentation and pilot testing involved several stages: preparation of the instruments, pretesting the instruments and other analytical techniques in the pilot study, analyzing the results of the study, and refinement of the instrument and techniques for use in the main study.

Instruments

To obtain data for the variables in the proposed integrated model, three separate test instruments were developed. Two of these instruments - Subconcepts Test and Volumetric Analysis Test were used to measure prerequisite concepts and achievement in volumetric analysis calculations respectively. The third test, the Classroom Proportionality Test was used to measure direct and inverse proportionality.
On each test, the following information was collected: (1) gender, (2) date of birth, (3) name, and (4) school. In addition to the above tests, a checklist and protocols were developed to assess the qualitative questions posed in the study. A brief description of each of the above instruments follows.

**Classroom Proportionality Test**

This is a 14-item group administered test used in assessing the proportional reasoning of subjects. It consists of two parts - a direct proportionality subtest and an inverse proportionality subtest.

Since the subtests assess two variables of interest in the study they are described separately.

The items in the inverse proportionality subtest were derived from a classroom test of formal operations developed by Lawson (1977, 1978). Lawson's test was chosen as a source of items because it is "at present the most appropriately validated test" (Nagy and Griffiths, 1979) with fairly high reliability (KR-20 is .78). In Lawson's test only two items were used to investigate inverse proportionality since his objective was to assess a wider range of formal operational thought. However, in the present study, in addition to the 1:2 and 2:3 situations investigated by Lawson, the inverse proportionality items were extended to include the following ratio situations - 1:3, 3:4, 3:5, 1:4 and 1:5. That is, seven items were constructed for the inverse proportion-
ality subtest. Following the procedure used by Lawson (1978) and Shayer and Wharry (1975), each item involved a demonstration using a balance beam and hanging weights (Inhelder and Piaget, 1958). For each item, the demonstration was used to pose a question to the class as a whole or call for a prediction. Each student responded to the questions in writing in his own test booklet. The test booklets contained only the questions followed by a number of possible answers. Students were instructed to respond by checking the box next to the best answer and then to explain why they chose the answer they had for each question. As noted by Lawson (1977), this demonstration procedure retains some important aspects of the clinical interview employed by Inhelder and Piaget (1958) (e.g. asking the students to explain their responses) while allowing for a large number of students to be tested in a relatively short time using a substantial number of problems.

The seven items in the direct proportionality subtest involved seven demonstrations using four plastic graduated cylinders of different diameters and a jar of coloured water. These items were also obtained from Lawson's test (Lawson, 1977, 1978). Apart from the 2:3 situation investigated by the two items in Lawson's test, the following ratio situations were investigated -- 2:5, 1:3 and 1:2. With the exception of the last situation, each situation involved two demonstrations and hence two test items. For each situation, subjects were allowed enough time to complete the item before the next demonstration was performed.
The validity of the items was established by Lawson (1977). He compared subject's performance on the written task with their performance on an interview task, the Equilibrium in the Balance Task.

Performance on the Classroom Proportionality Test was scored as follows: Those who selected the correct answer and reasoned using ratio or proportion were awarded three points. Those who used the correct reasoning i.e., ratio or proportion but selected the wrong answer were awarded two points. Subjects who selected the correct answer but used additive or any other reasoning or provided no reason were given one point while subjects who used wrong reasoning and selected a wrong alternative were scored zero. This was the same scoring procedure used by Lawson (Lawson, Nordland and DeVito, 1974).

Subconcepts Test

This was a test designed to test the knowledge of the content represented by the subsumed prerequisite concepts and hypothesized to be required for doing calculations in volumetric analysis. It consisted of a series of subtests representing each of the seven subordinate prerequisite concepts represented in Figure 5. The subordinate concepts in the figure were derived from the one proposed by Gower, Daniels and Lloyd (1977a). The only important difference between this figure and the one proposed by Gower, Daniels and Lloyd (see Figure 3), is that subordinate concepts requiring verbalization of definitions such as 'concentration' and 'molarity conventions' were not included in Figure 5. This was done for
Figure 5:
Hierarchical Analysis of Titration Calculations (Modified)
(Gower, Daniels, and Lloyd, 1977a)
two reasons: (1) to decrease the length of the test constructed because of time limitations in the schools, and (2) to ensure that only concepts of higher order are included since verbalization of definitions does not ensure understanding.

A description and illustrative example of each of the subordinate concepts labelled A to H in Figure 6 is presented below:

A. Determine the concentration or mass of one reactant involved in a titration from the concentration of another reactant and the reaction stoichiometry.
Example: 'What is the molarity of a hydrochloric acid solution 30.0 mL of which is neutralized by 48.0 mL of 0.10 M sodium hydroxide?'

B. Calculate the concentration of solutions from the mass of the substances.
Example: 'Calculate the molarity of a solution containing 5.0 mg of NaCl per mL of solution.'

C. Convert a solution from one concentration to another.
Example: 'Calculate the volume of 11.70 M hydrochloric acid solution that must be measured out to prepare 250 mL of a 0.20 M solution?'

D. Calculate the relative mass or moles of reactants and products from balanced equations.
Example: (a) 'How many grams of CO₂ are produced when 50.0 g of CaCO₃ is decomposed?'
(b) 'Calculate the grams of AgCl formed when 0.500 liter of 0.10 M AgNO₃ reacts with an excess of NaCl solution.'

E. Convert the mass of an element or compound to its number of moles, and vice-versa.
Example: 'How many moles of NaCl are present in 29.0 g of NaCl?'

F. Calculate the masses of different chemical elements or compounds containing the same or proportionate numbers of atoms or molecules.
Example: 'Calculate the mass of copper representing the same number of moles as 24.0 grams of carbon.'

G. Write balanced chemical equations using chemical symbols.
Example: 'Balance the following chemical equation:
\[ \text{CO} + \text{O}_2 \rightarrow \text{CO}_2 \]

H. Interpret balanced chemical equations in terms of number of moles, molecules or atoms of chemical species involved.
Example: 'What does the following equation mean:
\[ \text{C}_2\text{H}_5\text{OH} + 3\text{O}_2 \rightarrow 2 \text{CO}_2 + 3 \text{H}_2\text{O} \]'

Each subordinate concept was represented by four multiple choice (five-response) questions, thus yielding 28 items for the entire test. The items in the test were obtained from two sources. The first source was a test used by Wheeler and Kass (1977) to assess knowledge of introductory
chemical concepts such as the mole and stoichiometry. The other source was a test used by Johnstone and Duncan (1973) to identify students difficulties with certain chemical calculations including volumetric analysis, stoichiometry and gram mole conversions. The score of each student was indicated by the number of correct answers given for the items in the test.

**Volumetric Analysis Test**

This was a written test designed to test subject's ability to do volumetric analysis calculations. Eight items in the test were selected from Duncan and Johnston's (1973) test. Similar items were built to increase the total number of items to fifteen. The test items required subjects to calculate the volume, concentration or mass of one of the reactants involved in a titration. The subjects were asked to respond to the items by showing their answers as well as the steps used in their calculations. Achievement in this test was assessed by the number of correct answers obtained in the test independent of the procedures used. However, the calculations were examined for any conceptual errors that the students may have made. It was also used to identify those who used algorithms with understanding and those who used algorithms without understanding. In the study, using algorithms with understanding was defined as employing the correct stoichiometric or mole ratios in computations. Specifically, it referred to the use of 1:1 and 1:2 stoichio-
metric ratios in test items requiring them. Those who correctly employed this algorithm were referred to as using algorithms with understanding. Using algorithms without understanding was defined as employing incorrect stoichiometric or mole ratio in computations. Specifically, it referred to the use of 1:1 mole ratios in more than one computation requiring other mole ratios. Subjects using such strategies were considered to be using algorithms without understanding.

In addition to gathering psychometric data on the above instruments, the pilot study was also used to assess the effectiveness of a number of other analytical techniques used in the study.

Laboratory Skills in Titration

Two major approaches have been utilized in assessing student lab skills. These are checklists or rating scales (e.g. Tyler, 1942; Allen, 1972) and laboratory practical examinations (e.g. Kruglak, 1954). According to Doran (1978), the checklist approach is appropriate for identifying the manipulative techniques used by students in an interview situation. The checklist approach was therefore employed in this study. The task to which the checklist was applied is described in the next section.

The items in the checklist were based on the Manual Skills category referred to by Klopfer (1971) in his discussion of the evaluation of learning in science. Klopfer identified two subcategories under the Manual Skills. These are:
(a) development of skills in using common laboratory equipment and (b) performance of common laboratory techniques with care and safety. While the former is concerned with how the student manipulates various equipment, the latter is concerned with the carrying out of a series of manipulations to reach a desired goal. Examples under the first subcategory include manipulating glassware, such as pipettes and burettes. An example under the second subcategory would include the sub-skills required by a student when determining the volume of base required to react completely with a certain volume of an acid in titration. Some of these subskills are setting up the experiment, adding an indicator, and using a white background to detect colour changes. According to Klopfer (1971) "successful performance of these and other techniques calls for them to be done carefully, so that good results are obtained, and to be carried out with sufficient attention to safety to prevent injuring either the equipment or the experimenter" (italics added). This statement about good results and safety required the student, for example, to exercise caution near the end point of the reaction and also to use funnels in transferring solutions.

During the titration, this checklist was used by the investigator to identify the students' manual skills by checking off the items. In section A of the checklist, the overall skill used in handling the burette or pipette was summarized as inadequate, adequate or superior. If each of the three behaviours under a given section, say the burette, were
checked "yes", the subject was regarded as displaying superior skills. If only two of the included behaviours were present the subject was regarded as having adequate skills in handling the burette. However, if only one or none of the behaviours was checked "yes" the subject was regarded as having inadequate skills in handling the burette.

The Interview Task

To assess the subjects understanding of the concepts involved in an acid-base titration an individual interview approach was favoured since it allows one to probe further into a subject's initial responses. Following Piaget's procedure, a concrete task -- the titration of HCl against NaOH -- was used as the basis for eliciting the subject's responses. The task required the subject to determine the concentration of the HCl given the concentration of NaOH.

This task was broken down into two parts. The first part was to find the volume of base required to neutralize 25 ml of a given acid while the second part required the computation of the concentration of the acid from the data obtained from the first part.

The subjects were supplied with all the solutions needed for the titration including one indicator and a white sheet of paper. The solutions were HCl (approximately 0.1 M), and a dilute NaOH solution. The indicator used was bromthymol blue. The apparatus consisted of a 50 ml burette, a 25 ml pipette, a funnel, a burette stand, four 250 ml beakers and
four 250 ml conical flasks.

The concepts involved in an acid-base titration that were of interest in the present study were: pH, concentration, mole concept and indicator behaviour. Also of interest was the subjects' understanding of some of the chemical terminologies used in acid-base titrations. These included endpoint, stoichiometric point, equivalence point, and neutralization point.

To assess the above concepts and scientific terms in an interview situation, a number of questions were developed. These questions were based upon the procedures used in doing titration and the observations made by the subjects. Questions such as: "Why did you choose this indicator" and "Why does the indicator change colour" were asked, for example.

Two chemistry teachers who expressed interest in participating in the pilot study were asked to comment on the questions. Their major suggestion was to include a question on the pH at the stoichiometric point for the titration of a weak acid against a strong base.

To identify the strategies used by the students in their solution to the volumetric analysis calculations during the interview, the following question was asked: "How can you obtain the concentration of the HCl from the obtained data?" Since the interview task involved the titration of NaOH against HCl, the reacting mole ratio is 1:1.
Furthermore, in order to examine how the subjects used such titration data to predict the concentration of the acid in a problem situation requiring a mole ratio other than 1:1, three questions were used. These are:

1. If the acid reacted with the base in a mole ratio of 2:1 respectively, what will be the concentration of the acid?
2. If you used sulphuric acid in the titration instead of hydrochloric acid, what would be the concentration of the sulphuric acid?
3. If instead of sodium hydroxide, you had used sodium carbonate to titrate hydrochloric acid, what would be the concentration of the hydrochloric acid?

Pilot Study

Purpose

The purposes of the pilot study were: (1) to determine the psychometric properties of the Classroom Proportionality Test (CPT), Subconcepts Test (SCT) and the Volumetric Analysis Test (VAT); (2) to determine the appropriateness of the procedure used to identify the conceptual errors made on the VAT; and (3) to determine the appropriateness of the format of the interview on the titration task.

The Sample

The pilot sample consisted of 158 students in two secondary schools in the Vancouver metropolitan area and 5 first year university chemistry students. The secondary
school subjects belonged to six intact classes in the two schools. Forty subjects in two classes were enrolled in the Grade 11 chemistry course while the remaining subjects in four classes were enrolled in the Grade 12 chemistry course. The Grade 11 subjects were used because of the difficulty in obtaining Grade 12 classes in other schools.

The university subjects were asked to volunteer for the study. They were included in the study because at the time of the interview most Grade 12 chemistry students had not yet been formally introduced to laboratory techniques in volumetric analysis although they had done volumetric analysis calculations. The university students were thought to be similar to Grade 12 chemistry students in that prior to their participation in the pilot study, they had not done any titrations at the university.

Data Collection Procedure

In May 1980, the Volumetric Analysis Test and the Subconcepts Test were administered to the Grade 12 chemistry students. The four participating teachers were informed of the purposes of the pilot. They were encouraged to be critical of the tests and to indicate any sources of confusion in the format of the tests.

In September 1980, the Classroom Proportionality Test was administered to the two Grade 11 classes. The two teachers for these classes were asked to be present during the administration of the test so that they could provide their
comments on the instructions. They were also asked to comment on the format.

Immediately after the administration of this test, 8 students were randomly selected from the 40 students who took this test and interviewed on the Equilibrium in the Balance Task (Inhelder and Piaget, 1958). This was done to assess the validity of the Classroom Proportionality Test. The interview task involved the use of a balance beam and hanging weights to assess the proportional reasoning of subjects. The task required the subjects to simply restore the equilibrium of the balance by putting a specified weight at the correct point where these would counter-balance those placed by the interviewer. After placing the weights, the subjects were asked to explain their answers. Three different ratio situations were used. Performance on the Balance Task was assessed on the basis of the quality of the explanations and the ability to hang weights in the correct locations on the beam of the balance. The validity and reliability of the Equilibrium in the Balance Task have been established by numerous investigators (e.g. Bart, 1971; DeVries, 1974; Pumfrey, 1968; Lawson, Nordland and Devito, 1974).

Following the interview on the Equilibrium in the Balance Task, five university chemistry students were interviewed on the titration task. The interview was conducted in one of the lecture rooms in the Faculty of Education of the University of British Columbia.

The interview was divided into two major sections.
In the first part of the interview a type of Piagetian clinical interview technique (Piaget, 1929) was used to elicit the student's understanding of the concepts involved in titration. The subject was asked questions as he was performing the titration. He was also given a sheet of paper on which he could write. Also during this part of the interview a check-list, Laboratory Skills in Titration, was used to identify the manipulatory skills used by the subject as he performed the titration.

In the second part of the interview, the subject was asked to verbalize his thinking as he performed calculations and to predict the concentration of the acid in three problem situations.

The talking aloud technique or concurrent verbalization (Ericsson and Simon, 1980) employed in this study, has been used successfully by a number of investigators (e.g. Flaherty, 1974; Gorodetsky and Hoz, 1980) as an alternative approach to the question-and-answer technique in identifying the problem solving processes of subjects. It must be noted that although a review article by Nisbett and Wilson (1977) sought to criticize the use of this technique, a recent reanalysis of their paper by Ericsson and Simon (1980), using a model of verbalization which predicts the kind of content that can reliably be reported, showed that the experimental conditions and procedures used in most of the studies reviewed by Nisbett and Wilson were such that "verdical reports could hardly be expected" (Ericsson and Simon, 1980). Using their
model, Ericsson and Simon concluded that verbal reports elicited by asking subjects to think aloud produce a valuable and thoroughly reliable source of data about cognitive processes.

In the present study, after the subjects had completed the titration they were asked to think aloud as they used the obtained data to calculate the concentration of the acid. The subjects were given sheets of paper with their names on so that they could show their calculations on the sheets as they verbalized their thinking.

After calculating the concentration of the acid used in the titration, the subject was asked to use the data obtained in the titration to predict the concentration of the acid in three situations requiring a mole ratio of 2:1. This was done in order to find out if problem situations requiring the use of 2:1 reaction mole ratios would present any difficulties to the subjects -- that is, whether the subject realized the need to use the correct stoichiometric ratios in situations requiring their use. It was also done to find out if the same approach used in the initial situation requiring a 1:1 mole ratio was applied in these situations.

In these predictive situations, the subject was asked to use the volumes obtained in the titration and the known concentration of the base. After each prediction, the subject was asked to explain his prediction irrespective of whether he showed his calculations.

The above procedure, that is, asking for predictions
instead of asking subjects to perform more titrations was employed because of the length of the interview. The entire interview was audio-taped for subsequent transcription. Each interview took from 45 minutes to one hour for completion.

Scoring

In scoring the subtests of the CPT, 3 points were given for those subjects who selected the correct answer and reasoned in terms of ratio or proportion; 2 points were awarded to those who selected the wrong answer but used ratio or proportion in their explanation. Subjects who selected the correct answer but employed additive or any other explanations or no explanation were given a score of one. A zero score was awarded to those who selected the wrong alternative and gave the wrong reasons. The maximum score obtainable on each subtest of the CPT was 21.

The scoring procedure used for the Equilibrium in the Balance Task was similar to that for the CPT. The maximum score for the Equilibrium in the Balance Task was 9.

The scoring procedure used for the VAT and the SCT was to give one point for each correct answer. The maximum score obtainable on the VAT was 15 while the maximum score for the SCT was 28.

Data Analysis

Analysis was done separately for the test data and the interview data. In preparation of the test data for analysis by computer, the investigator coded the scores on fortran statement forms. Each student was given an identifica-
tion number that identified his grade, class and school. The score on the individual items of the tests taken by each student was also coded. The coded data were key-punched and verified by the Key-punching Services of the Computer Centre at the University of British Columbia. The data were hand-checked for key-punching errors by the investigator.

Item analysis was performed using the LERTAP (Nelson, 1974) computer program in order to determine the reliabilities of the VAT, SCT, and CPT and to examine the performance of the items in each test. The two subtests of the CPT were item-analyzed separately since they were treated as different variables in the study. The Statistical Package for the Social Sciences program (Nie, et. al. 1975) was used to obtain the correlation between the scores of the subjects on the CPT and the Equilibrium in the Balance Task.

The interview data were analyzed by first obtaining a complete transcript of the audio tapes. The responses of the subjects to each main question asked in the study were grouped together. For each question, responses which were similar were categorized together. These categories were called Response Patterns.

The interview protocols and the written work (obtained from the subjects when they were asked to work out solutions to several volumetric analysis problems using the data obtained from their titration) were analyzed to identify the approach (or strategy) used. As the students were asked to think aloud when doing these problems, the verbal protocols
along with their written responses were used to categorize the strategy they used in terms of a formula approach or a proportional reasoning approach.

The responses obtained when the subjects were asked to predict the concentration of the acid in three problem situations requiring 2:1 mole ratios were analyzed to see whether correct predictions were made.

The manual skills used by the subjects were examined to find the frequency of occurrence of each specific skill in the interview sample.

Finally, the written work of the subjects on the VAT was analyzed in order to identify the conceptual errors made in their solutions. For each subject, the individual steps used to solve each question on the VAT was examined for any errors in reasoning. Each conceptual error was recorded only once for any particular student regardless of whether he had made the same error on two or more other questions in the test.

Results and Discussion

Classroom Proportionality Test

Item Analysis: The item characteristics for the two subtests of the CPT are presented in Table 3. The item-subtest correlations revealed that all the item-test values for both the Direct Proportionality Subtest and the Inverse Proportionality Subtest were positive and high. This indicated that those who scored high on the subtest got the individual items correct.
Table 3

Test Statistics of the Classroom Proportionality Test

**SUBTEST A - DIRECT PROPORTION**

Test mean = 17.10
Highest score = 21.00
Hoyt estimate of reliability = 0.79
Standard error of measurement = 2.10

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point Biserial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62.5</td>
<td>0.74</td>
</tr>
<tr>
<td>2</td>
<td>60.0</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>87.5</td>
<td>0.53</td>
</tr>
<tr>
<td>4</td>
<td>82.5</td>
<td>0.69</td>
</tr>
<tr>
<td>5</td>
<td>87.5</td>
<td>0.80</td>
</tr>
<tr>
<td>6</td>
<td>87.5</td>
<td>0.59</td>
</tr>
<tr>
<td>7</td>
<td>82.5</td>
<td>0.61</td>
</tr>
</tbody>
</table>

**SUBTEST B - INVERSE PROPORTION**

Test mean = 10.20
Highest score = 21.00
Hoyt estimate of reliability = 0.84
Standard error of measurement = 2.21

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point Biserial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>42.5</td>
<td>0.49</td>
</tr>
<tr>
<td>9</td>
<td>47.5</td>
<td>0.62</td>
</tr>
<tr>
<td>10</td>
<td>32.5</td>
<td>0.78</td>
</tr>
<tr>
<td>11</td>
<td>32.5</td>
<td>0.78</td>
</tr>
<tr>
<td>12</td>
<td>53.0</td>
<td>0.80</td>
</tr>
<tr>
<td>13</td>
<td>30.0</td>
<td>0.82</td>
</tr>
<tr>
<td>14</td>
<td>25.0</td>
<td>0.83</td>
</tr>
</tbody>
</table>
The difficulty indices of the items in the two subtests revealed that the items in the Inverse Proportionality Subtest were more difficult than those in the Direct Proportionality Subtest.

The reliabilities for the Direct Proportionality and Inverse Proportionality Subtests were high (.79 and .84, respectively). This implies that there is an acceptable internal consistency among the items in each subtest.

**Validity:** The Pearson product moment correlation between the total scores of the subjects on the interview task - the Equilibrium in the Balance Task - and the Classroom Proportionality Test was calculated to be 0.91. The close correspondence between the two measures affirms that the Classroom Proportionality Test has convergent validity. This implies that the Classroom Proportionality Test can be used in place of the individual interview with reasonable confidence to measure proportional reasoning of subjects.

In administering the test one hour was found to be sufficient.

**The Subconcepts Test**

The results of the item analysis of this test are given in Table 4. The item-subtest correlations revealed that almost all the items possessed acceptable psychometric properties. Only one item in the subtest, Dilution Calculation, was found to have a correlation as low as 0.28. Examination of the calculations done by the subjects revealed that they did not read this question carefully.
Table 4
Test Statistics of the Subtests in the Subconcepts Test

<table>
<thead>
<tr>
<th>Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point-Biserial)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| SUBTEST A - CONCENTRATION CALCULATION
| Test mean = 3.20 | Standard deviation = 0.95 | Hoyt estimate of reliability = 0.49 |
| 1 | 82.7 | .65 |
| 2 | 93.8 | .43 |
| 3 | 85.2 | .64 |
| 4 | 58.0 | .76 |

SUBTEST B - DILUTION CALCULATION
Test mean = 2.02
Standard deviation = 1.04
Hoyt estimate of reliability = 0.30

| 5 | 53.1 | .67 |
| 6 | 71.6 | .71 |
| 7 | 61.7 | .56 |
| 8 | 76.0 | .28 |

SUBTEST C - STOICHIOMETRY
Test mean = 2.49
Standard deviation = 1.10
Hoyt estimate of reliability = 0.41

| 9 | 53.1 | .65 |
| 10 | 81.5 | .42 |
| 11 | 39.5 | .68 |
| 12 | 75.3 | .63 |

SUBTEST D - GRAM/MOLE CONVERSION
Test mean = 3.10
Standard deviation = .98
Hoyt estimate of reliability = .43

| 13 | 71.6 | .68 |
| 14 | 87.7 | .61 |
| 15 | 61.7 | .68 |
| 16 | 88.9 | .44 |
Table 4 continued ....

<table>
<thead>
<tr>
<th>Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point-Biserial)</th>
</tr>
</thead>
</table>

**SUBTEST E - MOLE**

Test mean = 2.62  
Standard deviation = 1.12  
Hoyt estimate of reliability = .40

<table>
<thead>
<tr>
<th>Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point-Biserial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>65.4</td>
<td>.52</td>
</tr>
<tr>
<td>18</td>
<td>58.0</td>
<td>.60</td>
</tr>
<tr>
<td>19</td>
<td>58.0</td>
<td>.67</td>
</tr>
<tr>
<td>20</td>
<td>80.2</td>
<td>.61</td>
</tr>
</tbody>
</table>

**SUBTEST F - BALANCING EQUATIONS**

Test mean = 2.04  
Standard deviation = 1.02  
Hoyt estimate of reliability = .43

<table>
<thead>
<tr>
<th>Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point-Biserial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>71.6</td>
<td>.75</td>
</tr>
<tr>
<td>22</td>
<td>46.9</td>
<td>.63</td>
</tr>
<tr>
<td>23</td>
<td>77.8</td>
<td>.64</td>
</tr>
<tr>
<td>24</td>
<td>7.4</td>
<td>.36</td>
</tr>
</tbody>
</table>

**SUBTEST G - INTERPRETATION OF REACTIONS**

Test mean = 2.41  
Standard deviation = 1.12  
Hoyt estimate of reliability = 0.40

<table>
<thead>
<tr>
<th>Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point-Biserial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>65.4</td>
<td>.59</td>
</tr>
<tr>
<td>26</td>
<td>49.4</td>
<td>.59</td>
</tr>
<tr>
<td>27</td>
<td>79.0</td>
<td>.54</td>
</tr>
<tr>
<td>28</td>
<td>46.9</td>
<td>.61</td>
</tr>
</tbody>
</table>

Reliability (Cronbachs alpha) for composite = 0.80
The reliabilities for the subtests were all below 0.5. This was attributed to the few items in each subtest. Also, the low reliabilities may be partially due to the nature of the subtest content. However, the reliability of the total test (Cronbach's composite alpha) was 0.80 which indicated that all the subtests may have been assessing the same content domain. The one hour allocated to this test was found to be sufficient.

The Volumetric Analysis Test

In this test, one item was found to have a correlation of 0.20. Further examination of this item suggested that the format of the question was likely confusing to some of the students. One item in the test was answered correctly by all subjects with the result that there was no discrimination on this item between the subjects who scored high on the test and those who scored low on the test. (Table 5)

The remaining items in the test were acceptable in terms of their item - total test correlations and difficulty coefficients. The reliability of the overall test was found to be 0.87. This reflects the internal homogeneity of the items in the test. One hour was found to be sufficient for this test.

Conceptual Errors

Six types of conceptual errors were found in the subjects' solutions to the items in the Volumetric Analysis Test. These were: (1) the assumption of 1:1 ratio in all
Table 5

Test Statistics of the Volumetric Analysis Test

Test mean = 10.26  \quad \text{Standard deviation} = 3.79
Highest score = 15  \quad \text{Lowest score} = 2
Hoyt estimate of reliability = 0.87
Standard error of measurement = 1.33

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Difficulty Index (%)</th>
<th>Discrimination Index (Point-Biserial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>77.8</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>77.8</td>
<td>0.44</td>
</tr>
<tr>
<td>3</td>
<td>6.3</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>70.4</td>
<td>0.63</td>
</tr>
<tr>
<td>5</td>
<td>100.0</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>48.1</td>
<td>0.87</td>
</tr>
<tr>
<td>7</td>
<td>48.1</td>
<td>0.88</td>
</tr>
<tr>
<td>8</td>
<td>33.3</td>
<td>0.77</td>
</tr>
<tr>
<td>9</td>
<td>66.7</td>
<td>0.45</td>
</tr>
<tr>
<td>10</td>
<td>63.0</td>
<td>0.75</td>
</tr>
<tr>
<td>11</td>
<td>81.5</td>
<td>0.49</td>
</tr>
<tr>
<td>12</td>
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</tr>
<tr>
<td>13</td>
<td>96.3</td>
<td>0.43</td>
</tr>
<tr>
<td>14</td>
<td>44.4</td>
<td>0.84</td>
</tr>
<tr>
<td>15</td>
<td>74.1</td>
<td>0.56</td>
</tr>
</tbody>
</table>
reactions; (2) the misconception that sulphuric acid will react with any base in a ratio of 1:2; (3) the notion that the concentration of a stock solution of acid is different from the concentration of the portion used in titration; (4) the reversal of the stoichiometric mole ratios; (5) the writing of incorrect formulas; and (6) the failure to write balanced chemical equations in the problem solutions.

The first conceptual error may be attributed to a number of possible factors including the use of incorrect formulas and the failure to write balanced chemical equations for the reactants.

The second conceptual error revealed that some of the subjects failed to discriminate between reactions in which \( \text{H}_2\text{SO}_4 \) reacted in a 1:2 and 1:1 mole ratios, respectively, with other substances. They only considered the two protons in \( \text{H}_2\text{SO}_4 \) without giving equal attention to the nature of the other reacting substances. Once again this difficulty might be attributed to the inability of some of the subjects to write correct formulas and correct balanced equations for the reacting substances.

The third conceptual error revealed that the subjects were applying a direct proportional relation to obtain a different concentration for the total solution. These students did not see the invariance of the concentration when only part of it has been removed. This implied that the subjects may not have had a good understanding of what a solution was. However, their difficulty could also have been viewed
as being structural in nature. That is, there is a part-whole relationship here. But this is not the commonsense one which implied that the whole is greater than one of its parts, since in this case the concentration of the total solution was the same as the concentration in a portion of it.

The fourth conceptual error -- reversal of mole ratios -- suggested that the subjects who made this error did not recognize the nature of the relationship between the stoichiometric coefficients and the moles of substances used in the reaction.

The fifth conceptual error -- writing incorrect molecular formulas -- suggested that the subjects who made this error probably did not understand the concept of valency. The written work of the subjects who made this error suggested that some of them, even though they could write the formulas for the compounds involved in the reaction, could not balance the equation. Other subjects failed to write equations in their solutions.

Laboratory Skills in Titration

The analysis of the laboratory techniques of the five university subjects revealed that three of the subjects who had done more than one titration in Grade 12 did not have any difficulties in proceeding with the experiment. They displayed reasonably accurate skills in the handling and reading of the burette and pipette, used a funnel in transferring solutions from the reagent bottles and exercised caution in adding the base. The other two students who had done only
one titration lab in Grade 12 had to be given some help. Despite the proper skills displayed in some areas by most of them only one subject realized the need for a white background to aid in observing the colour changes and no student washed down the acid solution adhering to the sides of the flask to ensure that all the acid reacted.

Other observations made were: three of the subjects asked for an extra burette to be used in measuring the acid solution, some of the students indicated that they were not familiar with the bromthymol blue indicator and hence asked for phenolphthalein, two students wrote down the volumes obtained in the titration only when they were prompted by the investigator.

The Interview Task

The analysis of the first part of the interview protocols which explored the subjects' understanding of titration concepts revealed a number of areas where the subjects did not seem to have clear understanding. In general, it was found that although, the subjects had a good understanding about concentration and moles, they did not have a clear understanding of pH, indicator behaviour and the scientific terms used in titration.

With respect to moles, only one of the five students indicated that the moles of the acid in a solution will be lower when distilled water is added. All the other questions on moles and concentration were correctly answered.
Most of the subjects realized that the pH at the stoichiometric point for the reaction between HCl and NaOH was 7. They also realized that the pH of the acid increased with the addition of the base. However, only two subjects could calculate the pH of .1 M NaOH or .1 M HCl. Also four of the subjects indicated that the pH for the reaction between acetic acid and NaOH was 7 while one student didn't know. Even though, they knew that the concentration of a solution will change with addition of distilled water, none of them realized that the pH will be higher.

Although they seemed to have a clear notion of why indicators are used in titration, they did not seem to understand the mechanism of indicator action. They also did not seem to know why bromthymol blue is used in the titration. Here, it must be noted, that since some of the students indicated that they were more familiar with phenolphthalein, the result could have been different if phenolphthalein had been used.

The terminology questions indicated that only one subject could explain what endpoint and stoichiometric point meant. However, all of them indicated that they had heard the term stoichiometric point. The difficulties of the subjects could be attributed to the fact that such questions are not usually asked during experiments, as was indicated by two students.

The analysis of the transcribed verbal protocols and the written work obtained from the subjects as they used
their own data to calculate the concentration of the HCl indicated that two basic approaches -- the Formula Approach and the Proportional Approach -- were employed by the subjects in the study. The basic form of the Formula Approach involved the use of the formula: Molarity x Volume = Moles, to calculate the moles of base initially and then use the value obtained and the mole ratio to find the moles of acid. The concentration of the acid was then found by a second application of the above formula but in this case using values for the acid. In a variant form of the Formula Approach, one subject used a formula which avoids a double application of the formula used in the basic form of the Formula Approach, namely, molarity of base x volume of base = molarity of acid x volume of acid. Thus, this variant form actually combines some of the steps in the basic form.

In the basic form of the Proportional Approach, the subject did not use an explicit formula but instead uses the proportional relation between moles and volume to obtain the moles of base. Using the reaction mole ratios, the moles of acid was then obtained. Thereafter, the same proportional relation between moles and volume was applied to the acid to obtain the concentration. The student who used a variant form of this approach employed a proportional relationship between the volumes and the concentrations of the acid and the base, namely,

\[
\frac{\text{Volume of acid}}{\text{Volume of base}} = \frac{\text{Molarity of base}}{\text{Molarity of acid}}
\]
This, in a sense, is a combination of the two proportions used in the basic form of the Proportional Approach. The analysis showed that two students used the basic form of the Formula Approach while one student used the variant form of the Formula Approach. For the remaining two students, one used the basic form of the Proportional Approach while the other used the variant form.

The analysis of the protocols on the subjects' prediction of the concentration of the acid from their data revealed that they had problems with reactions involving 2:1 mole ratios. It was found that while the initial problem involving NaOH and HCl in a 1:1 ratio was answered correctly by all subjects, three of the subjects failed to make correct predictions in the three situations although they used the same approach which gave them the correct answer in the initial problem. It was conjectured that this difficulty might be due to the inability to coordinate the stoichiometric mole ratio with other sources of information such as the actual moles of base used in the titration. However, this is not clear since the subjects were not asked to explain their predictions.

Revisions of the Instruments

Volumetric Analysis Test

Discussions with the teachers involved in the pilot study confirmed the ambiguity of the item in this test which had an item - total test correlation of 0.20. This item was modified to remove the ambiguity. Also, the one item with an item-subtest
correlation of zero was removed from the test because of its high difficulty index. It was however, replaced with an item from the test used by Duncan and Johnstone (1973). The final revised Volumetric Analysis Test (VAT) also consisted of 15 items (Appendix A). It appeared from the interview results, discussed above, that the number of laboratory titrations done by the subjects might influence their laboratory techniques and possibly their calculations. As such, subjects were asked to indicate the number of titrations they had previously done on the front page of the Volumetric Analysis Test.

Classroom Proportionality Test (CPT)

As a result of comments received from the participating teachers some wording changes were made in the instructions. Emphases were also placed on certain aspects of the testing procedure. For example, subjects were asked to pay particular attention to their explanations. They were also asked to pay attention while the investigator was performing demonstrations. This test and the testing procedures are presented in Appendix B.

The Subconcepts Test

For the subtest, Dilution Calculation, the item with a correlation of 0.28 was retained. However, during the administration of the test, students were asked to read the questions carefully. The Subconcepts Test (SCT) can be found in Appendix C.
Laboratory Skills in Titration

As a result of the observations made, students were supplied with three indicators -- bromthymol blue, phenolphthalein, and methyl orange -- from which they could choose one for the titration. Also, since some of them wanted to use a burette to measure out the volume of acid, an extra burette was included in the list of apparatus. Another item was included in the checklist in order to find out if the subjects recorded their volumes as soon as they were obtained. The final checklist, Laboratory Skills in Titration, consisted of 20 items (Appendix D).

The Interview Task

The revision of the interview protocols reflected in part, the additional indicators given to the subjects. A question was included which required the subject to explain his choice of indicator for the titration. Another question asked the subject to indicate whether the other indicators not chosen for the titration could be used. Other questions included in the interview required the subject to explain if there was any difference in the rate of change of the pH at the beginning of the titration and near the endpoint.

With the questions on terminology, the question on equivalence point was dropped since no subject seemed to have heard of it even though they had heard of stoichiometric point.

No revisions were made to the question requiring subjects to use their titration data to calculate the concentra-
tion of the HCl. However, with regards to the prediction questions, a further question was included to ask the subjects to explain their predictions. To improve the concreteness of the prediction questions, labelled solutions of sulphuric acid and sodium carbonate were included in the list of solutions. Solutions of acetic acid and ammonia were also included.

In general the pilot interview afforded an opportunity to assess the general format of the interview and provided some ideas about the understanding and skills that students bring into a titration situation. It also allowed the investigator to identify the approaches used by the subjects in their calculations.
CHAPTER IV

METHODS OF THE STUDY

Introduction

In this chapter, the instruments used, the population of interest, the sample, and the procedures employed in data collection and analyses in the study are described. Since the procedures for the selection of the sample of students who participated only in the model testing phase of the study (completed all written instruments) was closely related to the sub-sample selected for interviewing on the titration task, the sampling procedures and data collection procedures for both aspects of the study are described in this chapter. Also, the preliminary results conducted on the test data prior to the use of path analysis are included in this chapter.

Instruments

Student data on direct and inverse proportional reasoning, knowledge of prerequisite concepts and performance on volumetric analysis calculations were collected by adminis-
tering the Classroom Proportionality Test, Subconcepts Test, and Volumetric Analysis Test, respectively.

**Volumetric Analysis Test**

This test, pretested in the pilot study and described in the previous chapter, consisted of 15 items. The subjects were asked to calculate the concentration, volume or mass of one reactant from the known values of another reactant. The test measured the subjects' performance on volumetric analysis calculations.

**Classroom Proportionality Test**

The two subtests of this instrument were also pretested in the pilot study. Each of the subtests contained seven items. The Direct Proportionality subtest measured direct proportional reasoning while the subtest, Inverse Proportionality, measured inverse proportional reasoning.

**Subconcepts Test**

The subconcepts test, also pretested in the pilot study, contained seven subtests, each of which was represented by four items. Thus, the test contained a total of 28 items. This test measured the subjects' knowledge of the prerequisite concepts in volumetric analysis calculations.

**Population**

The present study was an analytical study primarily designed to investigate the difficulties that senior secondary
school students face when performing volumetric analysis calculations. Since volumetric analysis was only formally taught in the Grade 12 chemistry course of study in British Columbia, it was decided that students enrolled in the Grade 12 chemistry course in British Columbia would constitute the general population. However, the only area of British Columbia that was practical and available to carry out the study was the Lower Mainland. Thus for the purpose of this study, the students enrolled in Grade 12 chemistry courses in the Lower Mainland of British Columbia constituted the target population. Since Chemistry 12 is an optional course, normally only selected by more academically-oriented students, these subjects constituted a self selected group.

Sample

In May 1979, letters describing the objectives of the study and requesting permission to use selected schools in their district were sent to four School Boards in the Lower Mainland. Two School Boards showed immediate interest in the study. Schools within the jurisdiction of these School Boards were contacted by School Board representatives. Of the 21 schools contacted, 10 volunteered to participate in the study. The locations of the schools were such that a wide geographical representation was obtained in the sample. Furthermore, the catchment areas of these schools represented a wide diversity of socio-economic levels as assessed by the School Board officials. The students in the intact classes in
these schools constituted the sample for the study. There were initially 17 classes with a total student enrollment of 402 who wrote the first two instruments (CPT and SCT). However, due to logistical reasons (a delay in teaching the required unit on volumetric analysis) only eight schools with a total of 14 classes participated fully in the study, leaving a total number of subjects of 328 (203 boys and 125 girls).

**Data Collection Procedures**

The procedures used in the study related to the administration of tests to the participating students and the selection of students for interviewing.

**Test Administration**

In October and November, 1980, the Classroom Proportionality Test was administered by the investigator to all students in each selected class. The detailed procedure for administering this test can be found in Appendix B.

Following the administration of the above test, the Subconcepts Test was administered to the students in their intact classes to assess their knowledge of prerequisite concepts. Chemistry teachers participating in the study agreed to administer this test to their students as a review test before teaching volumetric analysis.

After teaching the unit on acids and bases which included volumetric analysis, the Volumetric Analysis Test was administered by the investigator to the students as an end-of-
unit test. In administering this test, the students were asked to show the steps they were using in their solution to the problems.

**Interview Sample**

One week after administering the final test -- the Volumetric Analysis Test -- the students in each school were grouped into high, medium and low achievement groups based on their scores on this test. Those who scored from zero to five were classified as low achievers, six to ten were classified as medium achievers and those scoring from eleven to fourteen as high achievers. In each school, two students were randomly selected from each group for the interview. Thus, six students were selected from each school, giving a total subsample of 48 subjects for the interview task. This was done to ensure that the subjects from the original sample were adequately represented. The students were interviewed individually in a separate room, usually the science preparation room. However, one student in the low achievement group in one school could not be interviewed because he was not available when other students in that school were interviewed; this left a total interview sample of 47.

**Interview Data Collection Procedure**

The final phase in the collection of data, the interviewing of the subsample, was scheduled about six to
seven days after the administration of the Volumetric Analysis Test. In consultation with the class teachers and the students, appointments were arranged for interviewing according to the convenience of the students.

The interviews were conducted by the investigator. At the beginning of the interview, the interviewer identified himself, indicated the intent of the interview and his affiliation to the University of British Columbia. The confidentiality of their responses was emphasized. The consent of each student was obtained before using the audio-tape recorder. The interviewer then proceeded with the interview according to the established protocols.

The interviewer showed the student the required apparatus and solutions for the titration task. The burette and the stand were left unassembled. Whilst the subject was doing the titration, the interviewer observed his laboratory techniques and completed the laboratory skills in titration checklist. The procedure employed during the interview can be found in Appendix E.

The sequence of events involved in the data collection for the entire study has been summarized in Figure 6 and Table 6.
Overall Design of Experimental Procedure

Figure 6
Table 6
Test Administration and Inter-test Breaks

| Tests administered prior to the teaching of volumetric analysis unit | CPT: | DP Subtest | 3 weeks | SCT | Interval during which volumetric analysis (VA) is taught | 2 months-5 months | Interval after teaching VA | 1 week | Test administered | VAT | Interval before inter-view | 7 days | Interval view period | 3 days-1 week |

Data Analysis

Data Preparation

For each student, the following data set was collected: number of laboratory titrations completed, direct proportionality test score, inverse proportionality test score, subconcepts test score, and volumetric analysis test score. The number of laboratory titrations completed was obtained by asking the subjects to indicate the number of titrations they had performed since Grade 11 on the front page of the Volumetric Analysis Test booklet. The values given by the students were checked with their teachers to ensure that no one overstated the titration laboratories completed. Other background data collected included school, class, and gender. After marking the Volumetric Analysis Test the investigator also categorized the subjects into a group who used the 1:1 stoichiometric ratio with understanding in solving the volumetric analysis problems.
and a group which did not use the stoichiometric ratio with understanding. This information was converted to numerical codes and recorded on fortran statement forms.

Data were key-punched and verified by the staff at the University of British Columbia Computer Centre. All the data were hand-checked for key-punching errors by the investigator. Errors were double-checked and corrected. In all, only five errors were detected.

**Scoring**

The same scoring procedure used in the pilot study (see Chapter III) for the proportionality tests, subsumed (prerequisite) concepts test, and volumetric analysis calculation test were employed in the main study. The scores for the two subtests of the Classroom Proportionality Test, namely, direct proportionality and inverse proportionality, were kept separate since each was considered as a different variable in the study.

**Preliminary Analyses of Data for Model Testing**

**Reliability of Instruments**

Item analyses and reliability estimation were performed on the Inverse Proportionality and Direct Proportionality subtests using the computer program LERTAP.

* Those subjects who wrongly applied a 1:1 mole ratio to more than two problems in the Volumetric Analysis Test were assumed to have used algorithms without understanding.
(Nelson, 1974). Subjects who were absent during the administration of any of the remaining tests but who took the CPT were eliminated before the item analysis was done. A similar procedure was carried out on the Subconcept and Volumetric Analysis Test scores.

Hoyt reliability index was calculated for the direct proportionality, inverse proportionality and Volumetric Analysis instruments. This reliability coefficient reflects on the internal consistency or homogeneity of the groups of items in each test or subtest.

The scores for the entire sample on the Direct Proportionality Subtest of the Classroom Proportionality Test ranged from 0 to 21. The Hoyt estimate of reliability for this subtest was 0.80. The difficulty index and discrimination index for each of the items in this subtest is reported in Appendix F. Table 7 gives the mean and standard deviation.

The scores for the sample on the Inverse Proportionality subtest also ranged from 0 to 21. Hoyt's estimate of reliability for this test was 0.93. The item statistics for this test are given in Appendix G.

The scores for the Subconcepts Test ranged from 0 to 28. Cronbach's composite alpha was calculated for this test in order to determine how the seven subtests hung together. The value for Cronbach's alpha was 0.78. This value reflects on the homogeneity of the items in the test. The item difficulty and the item-subtest correlations for the items in this test are reported in Appendix H.
The scores for the Volumetric Analysis Test ranged from 0 to 15. The Hoyt's reliability estimate was 0.88 (see Appendix I).

The reliabilities reported above for the instruments are comparable to those obtained in the pilot study (see Chapter III). Table 7 summarizes the statistics for the instruments.

Table 7
Summary Test Statistics For All 4 Tests

<table>
<thead>
<tr>
<th></th>
<th>DP</th>
<th>IPI.</th>
<th>SCT</th>
<th>VAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of items</td>
<td>7</td>
<td>7</td>
<td>28</td>
<td>15</td>
</tr>
<tr>
<td>Mean</td>
<td>18.75</td>
<td>13.92</td>
<td>19.04</td>
<td>7.08</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>4.07</td>
<td>7.29</td>
<td>4.91</td>
<td>4.23</td>
</tr>
<tr>
<td>Hoyt's reliability</td>
<td>0.80</td>
<td>0.93</td>
<td>0.78*</td>
<td>0.88</td>
</tr>
<tr>
<td>Standard error</td>
<td>1.68</td>
<td>1.84</td>
<td>2.04</td>
<td>1.39</td>
</tr>
</tbody>
</table>

* Cronbach’s composite alpha (Cronbach, 1951)

Differences of Classes

The data for all 328 subjects who participated in the study were screened to eliminate those who did not write all four tests. This left a final sample of 265 in 14 different classes, upon which the path analytical procedures were employed.
The SPSS subprogram CONDESCRIPTIVE (Nie, et. al. 1975) was used to obtain descriptive statistics (means and standard deviations) for the direct proportionality, inverse proportionality, subsumed concepts, and volumetric analysis test scores for each of the 14 classes (see Appendix J). Since the subjects belonged to certain classes it was necessary to test for possible differences among the classes for the direct proportion, inverse proportion, subsumed concepts and volumetric analysis scores before continuing with the analysis. Using the computer program OWMAR maintained by the Department of Psychology (U.B.C.), a multivariate test was performed on the differences in means among the classes and to test the tenability of the assumption of homogeneity of variance-covariance. Table 8 shows the results of this analysis.

Table 8
Test of Differences in Means and Homogeneity of Dispersion among Direct Proportionality, Inverse Proportionality, Sub-concepts and Volumetric Analysis Test Scores of Classes

<table>
<thead>
<tr>
<th>Test</th>
<th>DF1</th>
<th>DF2</th>
<th>F-Ratio</th>
<th>PROB</th>
</tr>
</thead>
<tbody>
<tr>
<td>MANOVA Likelihood Ratio Test for Differences among Means</td>
<td>52</td>
<td>963</td>
<td>3.8690</td>
<td>0.001*</td>
</tr>
<tr>
<td>Bartlett-Box Homogeneity of Dispersion Test</td>
<td>130</td>
<td>17348.1</td>
<td>1.4749</td>
<td>0.000*</td>
</tr>
</tbody>
</table>

*p < .05
These results indicate that the differences among the class means on all four variables is probably real. It also indicates that the null hypothesis that the variance-covariance matrix is the same for all classes is untenable. However, since this heterogeneity may be due to differences in variances, all the scores were standardized within classes to a mean of zero and standard deviation of one. The standardized scores were then analyzed using the OWMAR PROGRAM. The results as shown in Table 9 indicate that the transformation was successful in removing class differences. Consequently, all subsequent analyses were conducted using students' standardized scores and disregarding class as a factor, and the scores for all classes pooled together.

Table 9

Test of Differences in Means and Homogeneity of Dispersion among Direct Proportionality, Inverse Proportionality, sub-concepts and Volumetric Analysis Test Scores of Classes

<table>
<thead>
<tr>
<th>Test</th>
<th>DF1</th>
<th>DF2</th>
<th>F-Ratio</th>
<th>PROB</th>
</tr>
</thead>
<tbody>
<tr>
<td>MANOVA Likelihood Ratio Test</td>
<td>52</td>
<td>963</td>
<td>0.0019</td>
<td>1.000*</td>
</tr>
<tr>
<td>for Differences among Means</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bartlett-Box Homogeneity of Dispersion Test</td>
<td>130</td>
<td>17348.1</td>
<td>0.5969</td>
<td>0.999*</td>
</tr>
</tbody>
</table>

p > .05

* The scores for all the variables were transformed within classes to a mean of zero and a variance of one.
Before testing the model for the two groups of subjects, that is those who use algorithms with and without understanding, the scores were standardized separately.

**Path Analysis of Data**

Path models and other structural equation models have been evaluated in the past by using different procedures. The most popular of these procedures involves estimating and testing for the significance of the individual structural parameters. In this procedure, the fit of the model as a whole to the sample data is not evaluated - only the individual structural parameter estimates are evaluated (e.g. Gimmel, 1974). The non-significant paths are usually eliminated and the resulting modified (or trimmed) model is re-evaluated. In this procedure, the fit of the model as a whole is not evaluated. As Land (1973) has noted, the evaluation of structural models (i.e. models in which the causal directions are specified) based solely on the evaluation of the individual structural (path) coefficients may not always be applicable to the model as a whole especially when there are more than one over-identifying restrictions (i.e. more than one path has been eliminated). This is because it may be possible for some of the individual coefficients to be statistically significant while the test of the model as a whole may either
produce a significant or insignificant result. At other times, an investigator may eliminate a particular path which is statistically non-significant even though this path may be essential to the model as a whole. Land (1973), therefore, recommends the use of both the likelihood ratio chi-square statistic which tests the goodness-of-fit of the model as a whole and the individual Z (or t-) tests to evaluate the fit of structural paths. Other researchers (Bentler, 1980; Bentler and Bonett, 1980) have made similar suggestions. In addition, the examination of the residual covariance matrices has been suggested (e.g. Bentler, 1980).

The chi-square statistic provides a test of the proposed model against the saturated model, that is, the general alternative that the variables are simply correlated to an arbitrary extent. This, in a sense, is a chi-square difference test in that for the saturated model, since there is no over-identifying restriction, the degrees of freedom will be zero while the chi-square variate will also be zero. In this model appraisal, if the chi-square statistic is large compared with the degrees of freedom, it is concluded that the hypothesized model does not provide a plausible representation of the system of influences among the variables in the population. The converse will suggest that the model mirrors the causal processes that generated the data.

In the present analysis a combination of the above procedures was used to evaluate the proposed integrated model for the 265 subjects. The SPSS subprogram, REGRESSION (Nie,
et. al. 1975) was used for this analysis. This computer program estimates the structural parameters through equation-by-equation least squares procedure. However, programs like LISREL (Jöreskog and Sorbom, 1978) used the full information maximum likelihood method to estimate the parameters simultaneously. However, for recursive models with independent disturbances and no a priori cross-equation constraints, as is the case in the proposed model this method reduces to the equation-by-equation least squares solution (Land, 1973).

The chi-square test statistic used to evaluate the theory is given by Land (1973) for recursive models with independent errors and no cross-equation constraints as

$$N \sum_{g=1}^{G} \log \frac{\hat{\sigma}_{gg}^1}{\hat{\sigma}_{gg}^0}$$

where $\hat{\sigma}_{gg}$ is the estimate of the $g^{th}$ disturbance variance (i.e., the mean squared residual) obtained when $y_g$ is regressed on all antecedent variables and $\hat{\sigma}_{gg}^1$ is the estimate of the $g^{th}$ disturbance variance obtained when $y_g$ is regressed on all antecedent variables except those which are excluded a priori from the $g^{th}$ equation. $N$ is the sample size.

In evaluating the model, the proposed integrated model was first tested against the saturated model for the sub samples. The path coefficients, which reflect the strength of the influence of one variable on another, were also obtained and tested for significance. This proce-
dure was used for the subjects using algorithms with understanding (N = 105) and those using algorithms without understanding (N = 160). Details of this analysis are presented in the next chapter.

Analysis of Data for the Specific Student Difficulties

Analysis of Conceptual Errors

Initially each item in the Volumetric Analysis Test was scored 1 for correct answer and 0 for an incorrect answer. The steps used by the subject in his calculations were then examined for conceptual errors. The procedure used to identify the conceptual errors involved a critical examination of all the items in the test for each student. Since students were asked to show the steps used in each calculation, the analysis of the conceptual errors involved examining each step used by the subject and identifying the step(s) which produced the incorrect response. Items for which no explicit steps were shown but only the final answers were shown were eliminated from the analysis. Some subjects made explicit the steps used in their computations in only a few items. In all, every subject showed the steps for at least two items on the test. The following problem solution offered by Ben* serves to illustrate this type of analysis of the conceptual errors.

* All names used in the thesis are fictitious.
Question: A 500 mL solution of HCl is prepared for use in a class experiment. If 40.0 mL of this neutralizes 25.0 mL of 0.10 M Na₂CO₃ solution, what is the concentration of the original solution of HCl?

Ben's response:

Step 1: Na₂CO₃ + HCl

Step 2: 25.0 mL 40.0 mL
0.10 mol/L x mol/L

Step 3: 25.0 mL x 0.1 mol/L x \( \frac{L}{1000 \text{ mL}} \)
= 2.5 x 10⁻³ mol Na₂CO₃

Step 4: 2.5 x 10⁻³ mol Na₂CO₃ x \( \frac{1 \text{ mol HCl}}{1 \text{ mol Na₂CO₃}} \)
= 2.5 x 10⁻³ mol HCl

Step 5: Conc. = \( \frac{2.5 x 10^{-3} \text{ mol HCl} x 1000 \text{ mL}}{40 \text{ mL}} \)
= 6.25 x 10⁻² mol/L

Step 6: 6.25 x 10⁻² mol/L x \( \frac{1}{40 \text{ mL}} \) x 500 mL
= 7.8 x 10⁻¹ mol/L

Examination of Ben's calculation shows that no balanced equation is written, only the reactants are indicated (Step 1). However, in Step 4, Ben assumes that the stoichiometric mole relation between the two reactants is 1:1. In step 6, Ben assumes that the calculated concentration was for the 40 mL of the acid used in the reaction and hence calculates
the molarity for the 500 ml stock solution. Three conceptual errors can therefore be identified in Ben's solution. They are:

1) assumption of 1:1 mole ratio,
2) that the concentration of stock solution is different from the concentration of the volume used in the titration,
3) use of balanced chemical equations not considered in problem solution.

The results of the pilot study indicated the presence of these and other kinds of conceptual errors which could account for the incorrect answers on the items in the Volumetric Analysis Test. To check to see whether other people knowledgeable in this area would arrive at similar conceptual errors, twelve randomly selected answer booklets were given to a graduate student in chemistry to analyze in terms of the errors occurring in the solutions. Before doing the analyses, four students' answer booklets were used to instruct the other analyst about the intent of the analyses. It was emphasized that only the incorrect solutions should be analysed. It was also stressed that since for each subject all the items which had incorrect responses were to be analyzed, any one particular error identified for each subject should be indicated only once even though it may occur many times. That is, if a subject assumed 1:1 mole ratios in 3 problems requiring 2:1 mole ratios, this error was indicated only once. For the analyses of the 12 booklets an agreement ranging from 75.4 to 100% was obtained with a mean percent agreement of 91.5.
Discussion on the discrepancies in the analysis revealed that while for any one item on the test the investigator analyzed all the possible errors that could be identified, the other analyst identified only one conceptual error for each item on the test. To try to resolve this discrepancy six more answer booklets were analyzed. This produced a percent agreement of 95.4.

Analyses of Interview Data

The interviews with 47 students, using a laboratory-type titration task, generated data to address several different aspects about students' understanding of and potential difficulties with volumetric analysis. The different types of analyses used on these interview data are presented in the following sections while the results of these analyses are given in Chapter VI.

Manual Skills in Titration

Using the information from the checklist -- Laboratory Skills in Titration -- the manipulatory techniques used by all the subjects were tabulated (Appendix K). The presence or absence of each item on the checklist in the interview sample as a whole was then recorded in terms of the percentage of the sample using or not using a particular technique.

Ideas About the Concepts Involved in Titration

The tapes containing the interview data for the 47 students were transcribed verbatim by the investigator and the
graduate student who assisted in the analysis of the conceptual errors in the Volumetric Analysis Test. In trying to identify the ideas that subjects have about certain phenomena - objects and processes of nature - from protocols obtained in an interview setting, different analytic techniques have been applied by different researchers (Erickson, 1975). These analytic techniques range from the selection and classification of specific pertinent sections of the transcript (Piaget, 1929; Inhelder and Piaget, 1958) to more elaborate procedures which employ the entire transcript of the interview (e.g. Witz, 1970).

The analyses adopted in the present study is closely related to that of Piaget and others (e.g. Anderson, 1979). It involved identifying the pattern of responses expressed by a group of subjects to account for each major question posed by the investigator in the course of the interview. Questions which were used as 'starters' or 'linking questions' (Archenhold, 1979) were not analyzed. This analyses was applied to the first part of the interview.

Before isolating the response patterns, each subject's response for each question posed in the interview (Appendix L) was examined to identify the idea being expressed. A subject's idea (or notion) as used here is a statement or explanation offered by the subject to account for a problem situation initiated by the investigator. Thus they are the responses given verbally and in writing by the subject in answer to questions posed by the investigator.

The ideas expressed by each subject for each problem
situation (or question) was then examined in relation to other subjects' ideas about the same question. Ideas which seemed to go together or expressed similar intent were then grouped together under what is here referred to as a Response Pattern. In most cases, as could be seen by comparison of Appendix L and Tables 25 to 28 (presented in Chapter VI), these response patterns are direct reflections of the language used by the subjects.

Problem Solving Approach and Predictive Behaviour

In the second part of the interview, during which the subject was asked to verbalize his solutions, each subject's protocol was analyzed with the objective of identifying the approach used in solving the problem posed in this part of the interview. The problem required the subject to calculate the concentration of the acid from the data obtained from the titration. Thus, in the analyses of this section of the interview, the transcribed verbal protocols supported by the subject's written work provided the primary data. The analyses in the main study was similar to the one used in the pilot study. Essentially, the protocols and the written calculations were examined to isolate the steps used by the subject to solve the problem. To illustrate this analysis, Harry's verbal report and his written work will be used.

Verbalization:

"We have .1M of NaOH, we added 25.4 milliliters of it to the acid; and moles is concentration times volume. Therefore 25.4 times .1 is 2.54 millimoles of NaOH
which is the same as 2.54 millimoles of OH\(^-\) ions. And 1 mole of that (student points to the NaOH and HCl in a balanced equation he has written previously on the supplied paper) reacts with 1 mole of this. We must have 2.54 millimoles of acid or HCl reacting. We had 25 milliliters so therefore if we had 2.54 millimoles reacting ... (pause) ... We had 25 milliliters, we divide the moles into milliliters, no, by the milliliters; the milli cancel out and you have moles per liter which is concentration and you have about 2.54 divided by 25, that gives you concentration of .101. Concentration equals to 0.101 molar."

Written work: \(\text{NaOH} + \text{HCl} = \text{Na}^+ + \text{Cl}^- + \text{H}_2\text{O}\)

\[
0.1 \text{ mol/L NaOH} \times 25.4 \text{ mL} = 2.54 \text{ mmol NaOH}
\]

\[
\frac{2.54 \text{ mmol}}{25 \text{ mL}} = 0.101 \text{ M}
\]

\[= 0.10 \text{ M HCl}\]

From the above data, the relevant steps followed by Harry are: (i) write balanced chemical equation, (ii) substitute the volume and concentration of the base into a formula (Molarity x volume = moles) to obtain the moles of base used in titration, (iii) use the relation between the stoichiometric ratio of the reactants in the equation and the moles of base used in the reaction to obtain moles of acid, (iv) rearrange the formula applied previously and substitute values into it to obtain the molarity of the acid. From this, Harry was described as employing the basic form of the Formula Approach. Similar analyses were applied to the data for all the subjects involved in the interview.

In addition to asking the subjects to verbalize their solutions in this part of the interview, the subjects were also asked to make predictions and offer reasons for their predictions for three problems involving a 2:1 mole
ratio between reactants. The protocols obtained from asking the subjects to predict the concentration of the acid in these three related problem situations (using the data they had obtained in the titration) were analyzed in terms of the type of prediction and the explanation offered by the subjects. Analysis showed that the same approach that was used in obtaining the molarity of the hydrochloric acid in the initial situation involving 1:1 reacting ratios were used in responding to the prediction questions. It was also found that those who initially had difficulty in calculating the molarity of HCl in the 1:1 situation, especially those classified as using the NC (not comprehensible) Approach made the same errors in their calculations with the prediction questions even though they occasionally made the correct predictions and offered appropriate explanations in some cases.

A further analysis was done to show the changes in predictions in the three situations with respect to the approach employed. This analysis attempted to provide a clear diagramatic representation of the possible conceptual paths followed by the subjects in making their predictions.

**Performance on VAT and Number of Titration Experiments**

Correlation analysis using the Statistical Package for the Social Sciences (Nie, et. al., 1975) was performed on the number of titration experiments done by the students prior to the study and their scores on the Volumetric Analysis Test (VAT). This analysis was performed for the 265 subjects who
completed all the tests administered in the study. This was
done to find out the nature of the relationship between these
two variables.
CHAPTER V

RESULTS AND DISCUSSION OF MODEL TESTING

Introduction

In this chapter, the results and interpretation of the analyses conducted to answer the research questions related to the validation of the proposed integrated model are presented. The statistical hypotheses corresponding to these research questions are presented first. Since the preliminary analysis of the data showed that there might be a difference among the students in terms of their use of stoichiometric ratios in calculations, the test of the proposed integrated model was performed on the two groups of subjects identified in the study. As will be shown, differences were observed among these two groups. Therefore the test of the model for the total sample was deleted.

For reasons of brevity, the variables, direct proportional reasoning, inverse proportional reasoning, knowledge of subsumed or prerequisite concepts, and performance on volumetric analysis calculations will be designated by DP, IP, SC, and VAC respectively, in this chapter.
As used in this chapter, the term saturated model will refer to a model similar to the proposed integrated model but with an assumed causal connection between direct proportional reasoning and performance on volumetric analysis calculations. Trimmed (or modified) integrated model will refer to the final model resulting from the deletion of some of the causal connections in the proposed integrated model.

Evaluation of the Integrated Model

Statistical Hypotheses

1. Model Evaluation for Total Sample

The hypothesized integrated model accounts for the total sample data.

However, as will be shown in testing the second hypothesis, differences in some of the path coefficients were found among the two groups. Because of these differences the pooling of the scores from the two groups may lead to confounded results. Hence no analysis was performed on the total sample.

2. Model Evaluation for the Two Groups

The two groups of subjects considered in this study were those subjects who used algorithms with understanding and those who used algorithms without understanding.

(a) The proposed integrated model explains the observation data for the subjects who use algorithms with understanding.

(b) The proposed integrated model explains the observation data for the subjects who use algorithms without understanding.
These hypotheses for the two groups were tested at the .05 level of significance and correspond to research questions in Chapter I.

**Model Evaluation for Subjects Using Algorithms Without Understanding**

The analysis of the sample data (Table 10) for the subjects who applied the 1:1 mole ratio indiscriminately yielded the parameter estimates reported in Table 11.

**Table 10**

Covariance Matrix for Subjects Using Algorithms Without Understanding (N = 160)

<table>
<thead>
<tr>
<th></th>
<th>VAC</th>
<th>SC</th>
<th>IP</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAC</td>
<td>(1.000)*</td>
<td>(0.405)</td>
<td>(0.122)</td>
<td>(-0.053)</td>
</tr>
<tr>
<td></td>
<td>0.994</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td></td>
<td>(1.000)</td>
<td>(0.378)</td>
<td>(0.196)</td>
</tr>
<tr>
<td></td>
<td>0.403</td>
<td>0.994</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td></td>
<td></td>
<td>(1.000)</td>
<td>(0.386)</td>
</tr>
<tr>
<td></td>
<td>0.122</td>
<td>0.376</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>DP</td>
<td>-0.053</td>
<td>0.195</td>
<td>0.383</td>
<td>(1.000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.994</td>
</tr>
</tbody>
</table>

*Correlations in parentheses*
Table 11
Parameter Estimates, Standard Errors (SE) and Critical Ratios (CR) for Subjects using Algorithms Without Understanding (N = 160)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>SE</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{43}</td>
<td>0.419</td>
<td>0.078</td>
<td>5.372*</td>
</tr>
<tr>
<td>P_{42}</td>
<td>-0.036</td>
<td>0.078</td>
<td>-0.462</td>
</tr>
<tr>
<td>P_{32}</td>
<td>0.355</td>
<td>0.079</td>
<td>4.494*</td>
</tr>
<tr>
<td>P_{31}</td>
<td>0.059</td>
<td>0.079</td>
<td>0.747</td>
</tr>
<tr>
<td>P_{21}</td>
<td>0.386</td>
<td>0.073</td>
<td>5.288*</td>
</tr>
</tbody>
</table>

* P < .05

Note: Model $\chi^2 = 2.3668$ (df = 1), $P > .05$

The estimates presented in Table 11, are symbolized by $P_{ij}$ which represents the effect of variable $j$, the independent variable, on variable $i$, the dependent variable in the model. Table 11 also gives the standard error and critical ratios for each parameter estimate. Each critical ratio is a $t$-ratio representing the ratio of the parameter estimate minus the null value of zero to its standard error. The critical ratios provide an indication of the importance of each parameter estimate in the proposed integrated model. The values for the critical ratios suggest that two paths, namely, the influence of indirect proportion on performance in volumetric
analysis calculations and the influence of direct proportion on knowledge of subsumed prerequisite concepts are statistically insignificant and hence may not be important to the model. All remaining estimates are essential to the model.

In Figure 7, which is a diagrammatic representation of the integrated model, the numerical values of the path coefficients are indicated on the individual paths. Also indicated in parentheses in the figure are the standard errors corresponding to each path coefficient.

The chi-square test of the fit of the proposed integrated model yielded a chi-square value of 2.3668 with 1 degree of freedom (see Table 11). This value is not signi-

* Standard errors in parentheses

Figure 7: Integrated Model for Subjects Using Algorithms Without Understanding.
ificant at the 5% level of significance. This indicates that the model cannot be distinguished statistically from the saturated model in which there is no over-identifying restriction (i.e. all the causal connections are assumed to be present). This suggests that the model offers a plausible explanation of the variance-covariance matrix in this subsample. The residual matrix resulting from the deviation of the reproduced covariance matrix from the sample covariance matrix (for the proposed integrated model) is given in Table 12. The table also gives the reproduced covariance matrix for the integrated model. Examination of this matrix reveals that almost all the sample covariances have been explained by the proposed integrated model.

The result of the chi-square test suggests that all the causal paths, taken together, may be important to the model as a whole. However, as the test of the individual path coefficients revealed, the paths between DP and SC and between IP and VAC may not be very crucial in explaining the test scores for the subjects who use algorithms without understanding even though when considered together with the other paths, they appear to be important.

As other researchers (e.g. Kerlinger and Pedhazur, 1973, pp. 317 – 318; Heise, 1969, pp. 59 – 60) have suggested, the goals of structural modelling may include model trimming - that is, the removal of paths which are statistically insignificant from the model. This is done in order to assess whether a more parsimonious model could account reasonably
Table 12

Residual Matrix Resulting from the Difference between the Sample Covariance Matrix and the Reproduced Covariance Matrix for Subjects using Algorithms Without Understanding

<table>
<thead>
<tr>
<th></th>
<th>VAC</th>
<th>SC</th>
<th>IP</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAC</td>
<td>(0.994)*</td>
<td>(0.403)</td>
<td>(0.122)</td>
<td>(0.068)</td>
</tr>
<tr>
<td></td>
<td>0.000</td>
<td>[0.000]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>[0.000]</td>
<td>[0.000]</td>
<td>[0.000]</td>
<td>[0.000]</td>
</tr>
<tr>
<td>IP</td>
<td>-0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>(0.994)</td>
</tr>
<tr>
<td></td>
<td>[-0.031]</td>
<td>[0.000]</td>
<td>[0.000]</td>
<td>[0.383]</td>
</tr>
<tr>
<td>DP</td>
<td>-0.121</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>[-0.112]</td>
<td>[0.050]</td>
<td>[0.000]</td>
<td>[0.000]</td>
</tr>
</tbody>
</table>

* Reproduced covariances in parentheses
+ Residual matrix for trimmed model in square brackets

well for the data. Following this procedure, the path between indirect proportion and performance on volumetric analysis calculations and the one between direct proportion and knowledge of subsumed prerequisite concepts were deleted from the proposed integrated model. The resulting model, which is referred to as the trimmed integrated model (or the Z-model), is represented in Figure 8.

Analysis of the data in terms of the trimmed integrated model yielded the parameter estimates given in Figure 8 and Table 13. The critical ratios show that all the
Table 13

Parameter Estimates, Standard Errors (SE) and Critical Ratios (CR) of Trimmed Integrated Model for Subjects using Algorithms without Understanding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>SE</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>P43</td>
<td>0.406</td>
<td>0.072</td>
<td>5.639*</td>
</tr>
<tr>
<td>P32</td>
<td>0.378</td>
<td>0.073</td>
<td>5.178*</td>
</tr>
<tr>
<td>P21</td>
<td>0.386</td>
<td>0.073</td>
<td>5.288*</td>
</tr>
</tbody>
</table>

* P < .05

Note: Model $\chi^2 = 2.0215$ (df = 3), P > .05

Total Effects

VAC-DP = P21 P32 P43

= 0.059

VAC-IP = P32 P43

= 0.153

SC-DP = P21 P32

= 0.146

* Standard errors in parentheses

Figure 8: Trimmed Integrated Model for Subjects using Algorithms without Understanding
paths are essential to the model. The chi-square goodness-of-fit test for this modified model gave a value of 2.0215 (df = 3) which was not statistically significant at the 5% level. This indicates that the trimmed integrated model also provides a plausible representation of the observed data. Further examination of its residuals (Table 12) revealed that the trimmed integrated model accounts for a substantial proportion of the covariances in the matrix. Residuals close to zero are not unexpected since the trimmed integrated model assumes that these covariances are zero. Thus, it would appear from the two sets of results that both models are plausible representation of the data.

To further clarify this situation, a detailed analysis was performed to examine the total associations among the variables in the proposed integrated model. The results of this analysis are presented in Table 14. In this table, the total association between any two variables has been decomposed into indirect and direct effects, total effects, and spurious effects. Spurious effects between two variables refer to the compound paths that are mathematically part of the decomposition but may be due to the presence of a common cause or the presence of causes which are correlated (Alwin and Hauser, 1975). The total effect is that part of the total association between two variables which is not due to spurious effects. The direct effect is that part of the total effect which is not transmitted via intervening variables, while the indirect effect is that part of a variable's total effect which is mediated by intervening variables.
Table 14

Effects Analysis in the Integrated Model for Subjects using Algorithms without Understanding

<table>
<thead>
<tr>
<th>Pre-determined Variables</th>
<th>Dependent Variable</th>
<th>Total Effect</th>
<th>Direct Effect Via</th>
<th>Indirect Effect Via</th>
<th>Spurious Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>VAC</td>
<td>0.419</td>
<td>-</td>
<td>-</td>
<td>-0.014</td>
</tr>
<tr>
<td>IP</td>
<td></td>
<td>0.113</td>
<td>-0.036</td>
<td>0.149</td>
<td>0.009</td>
</tr>
<tr>
<td>DP</td>
<td></td>
<td>0.068</td>
<td>-</td>
<td>-0.014 0.025 0.057</td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td>SC</td>
<td>0.355</td>
<td>-</td>
<td>-</td>
<td>0.023</td>
</tr>
<tr>
<td>DP</td>
<td>SC</td>
<td>0.196</td>
<td>0.059</td>
<td>0.137</td>
<td>-</td>
</tr>
<tr>
<td>DP</td>
<td>IP</td>
<td>0.386</td>
<td>0.386</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The effects decomposition in Table 14 was obtained using Wright's (1934) procedures and the fundamental theorem of path analysis (Duncan, 1966). The values obtained from these procedures were confirmed by using the simpler procedure due to Alwin and Hauser (1975).

The results shown in Table 14 show that the indirect effect of DP on SC (0.137) is far greater than its direct effect (0.059). This indirect effect accounts for about 70% of the total effect. This is even greater for the trimmed integrated model (see Figure 8). The effects analysis also revealed that for the subjects who use algorithms without understanding, inverse proportional reasoning may be suppressing the effect of direct proportional reasoning on volumetric
analysis calculations. This is shown by the value of \(-0.014\) for the mediating effect of inverse proportional reasoning. However, in an interactive system, when one variable is found to suppress the effect of another, the converse situation could also be said to exist since suppression is "fully symmetric or mutual" (Cohen and Cohen, 1975, pp. 89-90). The choice of the direction of the suppression becomes then one of meaningfulness (Cohen and Cohen, 1975, pp. 89-90).

Applied to the present problem, it could be argued that direct proportional reasoning may be the suppressor variable. This is suggested by the negative value \((-0.143\) obtained for the direct effect of direct proportional reasoning on volumetric analysis calculations when this path is included in the proposed integrated model. Because of this suppressing effect of direct proportional reasoning on the influence of inverse proportional reasoning (IP) on volumetric analysis calculations (VAC), the direct effect of IP on VAC is negative. Also the indirect effect of direct proportional reasoning on VAC via IP is negative because of this suppression. This may be important since some of these subjects were found in the interview to incorrectly apply a direct proportional relation between molarity and volume of solution when solving the volumetric analysis problems, even though they could reason in terms of inverse proportion. Also, those subjects in this group who obtained the correct reacting ratios had difficulty in solving the problems because they 'reversed' the mole ratios in their calculations. That is, these subjects
incorrectly assumed an inverse relation between stoichiometric coefficient and moles of the reacting substances.

The substantive meaning of the deleted paths in the trimmed integrated model is that direct proportional reasoning does not influence knowledge of prerequisite concepts directly and that inverse proportional reasoning does not have a direct influence on performance in volumetric analysis calculations. This seems to be contrary, in some sense, to some of the theoretical analyses performed on some chemical concepts. For example Herron (1975) analyzed some chemical concepts including volumetric analysis calculations and concluded that students will have difficulties in doing volumetric analysis-type calculations because of the inverse proportionality involved. He implied by his analysis that successful performance on such a problem will require the ability to reason using indirect proportion. The empirical result obtained for the trimmed integrated model suggests that indirect proportional reasoning does not have any direct effect on performance in volumetric analysis calculations. Its influence is mainly through the knowledge of the subsumed concepts. Even the result for the proposed integrated model reveals, as already noted above, that the mediating effect of subsumed concepts on volumetric analysis calculations is very substantial. This result is understandable in view of the suggestion in the literature that the content of a task may interact with reasoning ability of the subjects on the task (e.g. Lunzer, 1975).
Ingle and Shayer (1971) also analyzed the mole concept and its associated calculations and concluded that since the mole concept involves proportional (really, direct proportional) reasoning, high school students who can't reason in this way will find it difficult to comprehend these concepts. This analysis implies a direct effect of direct proportional reasoning. The above empirical result for the trimmed integrated model indicates, however, that direct proportional reasoning does not have any direct effect on the prerequisite concepts (which includes the mole concept). It treats its effect on subsumed concepts solely as being transmitted via inverse proportional reasoning.

It could be that, since direct proportional reasoning precedes and is subsumed by inverse proportional reasoning, most of the effect of direct proportional reasoning or subsumed concepts is transmitted through inverse proportional reasoning as soon as this latter reasoning ability is developed. Also, it seems reasonable to hypothesize that with tasks involving solely direct proportions or simple ratios, the unmediated influence of direct proportional reasoning may be considerable (i.e. direct proportional reasoning will be displayed in the solution to the task). But where formulas or algorithms could be applied this direct effect may become small. Similarly, the direct influence of inverse proportional reasoning may become important in tasks requiring its use. However, where there is a formula which
could be applied as in the case of volumetric analysis calculations, this direct effect may diminish while its effect through the application of the formula may become substantial.

Also the above results indicate that in both the original model and the trimmed model, direct proportional reasoning has a direct influence on inverse proportional reasoning. This is consistent with the results obtained by others (Rogers, 1977). It also suggests that direct proportional reasoning precedes inverse proportional reasoning in acquisition. It suggests further that inverse proportional reasoning influences knowledge of subsumed prerequisite concepts which in turn affects performance on volumetric analysis calculations. The significant effect of subsumed prerequisite concepts compared with inverse proportional reasoning on performance in volumetric analysis calculations, is not unexpected since in the studies by Wheeler and Kass (1977) and Griffiths (1979) subsumed concepts (or content) were found to be more important than the reasoning ability of the subjects.

It has been suggested that in the evaluation of structural models, apart from the computation of statistics and the examination of residuals, the theory and meaningful interpretation should dictate the choice of model. From the above discussion of the results, it seems the trimmed integrated model would be preferable to the proposed integrated model on the grounds of meaningfulness and parsimony. It has been argued that,
"the potential for refining or trimming a theory, and thus making the theory more parsimonious, clearly is of considerable significance and could be listed along with the issues of explanation ... as a basic gain to be acquired from the construction of linear models." (Heise, 1969, pp. 59-60).

It is seen also that the trimmed integrated model is consistent with the kinds of formulations usually made in the science education literature in terms of the explanatory variables (structure and content) used to rationalize students' understanding of school concepts (Wheeler and Kass, 1977; Herron, 1975; Johnstone, MacDonald and Webb, 1977). However, cognisance is taken of the fact that for these subjects direct proportional reasoning may be suppressing the effect of inverse proportional reasoning.

The results for the subjects who tended to use incorrect stoichiometric ratios in their calculations seem to suggest (as explained above) that, with these subjects the ability to reason using direct proportion may be hiding the true effect of their inverse proportional reasoning ability in volumetric analysis calculations. It could be argued that since some of these subjects (as borne out by the interview data discussed later) assume a direct proportional relation instead of an inverse one between molarity and volume even though they can reason using inverse proportion, this ability to reason using inverse proportion tends to have a slight negative influence on their performance on volumetric analysis calculations. It is suggested that this behaviour of the subjects may reflect on the structural complexity of volumetric analysis problems -- that is, the fact that it involves both
direct and inverse relationships. As such the students probably become confused over which relation is applicable between which two variables.

Again, it is suggested here that the strong influence of prerequisite concepts on volumetric analysis calculations for these subjects may mean that the mediating influence of prerequisite concepts may be essential to their performance on the calculations since they tend to get confused over which structural relation they have to use. It could be that some of these subjects employ formulas in their solutions with an understanding of the basic concepts involved thereby increasing the influence of the subconcepts on performance on volumetric analysis calculations.

Model Evaluation for Subjects Using Algorithms With Understanding

The validation of the proposed integrated model for subjects using algorithms with understanding gave the parameter estimates, standard errors, and critical ratios presented in Table 15. These values were obtained from the analyses of the sample variance-covariance matrix for this subsample (Table 16). As the values indicate, with the exception of the path coefficient between direct proportional reasoning and knowledge of subsumed prerequisite concepts, all other parameters are important to the proposed integrated model. That is, only direct proportional reasoning has statistically insignificant direct influence on knowledge of subsumed prerequisite concepts.
Table 15
Parameter Estimates, Standard Errors (SE) and Critical Ratios (CR) for Subjects using Algorithms with Understanding. (N' = 105)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>SE</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>P&lt;sub&gt;43&lt;/sub&gt;</td>
<td>0.214</td>
<td>0.104</td>
<td>2.058*</td>
</tr>
<tr>
<td>P&lt;sub&gt;42&lt;/sub&gt;</td>
<td>0.208</td>
<td>0.104</td>
<td>2.000*</td>
</tr>
<tr>
<td>P&lt;sub&gt;32&lt;/sub&gt;</td>
<td>0.429</td>
<td>0.095</td>
<td>4.515*</td>
</tr>
<tr>
<td>P&lt;sub&gt;31&lt;/sub&gt;</td>
<td>0.123</td>
<td>0.095</td>
<td>1.295</td>
</tr>
<tr>
<td>P&lt;sub&gt;21&lt;/sub&gt;</td>
<td>0.439</td>
<td>0.088</td>
<td>4.989*</td>
</tr>
</tbody>
</table>

* P < .05

Note: Model \( \chi^2 = 0.9183 \) (df = 1), P > 0.05

Figure 9 gives the integrated model and the parameter estimates.

A test of the model as a whole for these subjects using the chi-square goodness-of-fit test yielded a chi-square value of 0.9183 with 1 degree of freedom (Table 15). This value is not significant at the .05 level of significance, suggesting that the model is representative of the processes underlying the sample data. The residual matrix resulting from the deviation of the reproduced covariance matrix from the sample covariance matrix is given in Table 17. The examination of this matrix shows that virtually no residuals are left behind.
Table 16

Covariance Matrix for Subjects using Algorithms with Understanding (N = 105)

<table>
<thead>
<tr>
<th></th>
<th>VAC</th>
<th>SC</th>
<th>IP</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAC</td>
<td>(1.000)</td>
<td>(0.315)</td>
<td>(0.312)</td>
<td>(0.184)</td>
</tr>
<tr>
<td></td>
<td>0.990</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>0.311</td>
<td>(1.000)</td>
<td>(0.483)</td>
<td>(0.311)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td>0.308</td>
<td>0.478</td>
<td>(1.000)</td>
<td>(0.439)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.990</td>
<td></td>
</tr>
<tr>
<td>DP</td>
<td>0.182</td>
<td>0.308</td>
<td>0.435</td>
<td>(1.000)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.990</td>
</tr>
</tbody>
</table>

* Correlations are in parentheses

Figure 9: Proposed Integrated Model for Subjects Using Algorithms with Understanding.
Table 17

Residual Matrix Resulting from the Difference between the Sample Covariance Matrix and the Reproduced Covariance Matrix for Subjects Using Algorithms with Understanding

<table>
<thead>
<tr>
<th></th>
<th>VAC</th>
<th>SC</th>
<th>IP</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAC</td>
<td>(0.990)*</td>
<td>(0.311)</td>
<td>(0.308)</td>
<td>(0.156)</td>
</tr>
<tr>
<td></td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.000]*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.000]</td>
<td>[0.000]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.000]</td>
<td>[0.000]</td>
<td>[0.000]</td>
<td></td>
</tr>
<tr>
<td>DP</td>
<td>0.026</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td></td>
<td>[0.047]</td>
<td>[0.098]</td>
<td>[0.000]</td>
<td>[0.000]</td>
</tr>
</tbody>
</table>

* Reproduced covariances in parentheses

+ Residual matrix for the trimmed model in square brackets

Although the residuals and the chi-square test indicate that all the paths among the variables may help in explaining the covariances in the sample data, the test of the individual paths shows that the path between DP and SC may not count very much in this explanation.

The next stage in the analysis therefore, was to apply model trimming procedures to find if a trimmed model could be obtained which is more representative of the sample data than the proposed integrated model. Since the path
between direct proportional reasoning and knowledge of subsumed concepts was not significant, it was deleted and the model re-analyzed. The estimates obtained are presented in Table 18.

Table 18

Parameter Estimates, Standard Errors (SE) and Critical Ratios (CR) of Trimmed Integrated Model for Subjects using Algorithms with Understanding

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>SE</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{43}</td>
<td>0.214</td>
<td>0.104</td>
<td>2.058*</td>
</tr>
<tr>
<td>P_{42}</td>
<td>0.207</td>
<td>0.104</td>
<td>2.000*</td>
</tr>
<tr>
<td>P_{32}</td>
<td>0.483</td>
<td>0.086</td>
<td>5.616*</td>
</tr>
<tr>
<td>P_{21}</td>
<td>0.439</td>
<td>0.088</td>
<td>4.989*</td>
</tr>
</tbody>
</table>

Note: Model \( \chi^2 = 1.5859 \) (df = 2), \( P > .05 \)
* \( P < .05 \)

A diagrammatic representation of the trimmed model is given in Figure 10. As indicated in Table 18, all the parameter estimates are significant at the five percent level, suggesting that all the paths are probably real. The chi-square test for this trimmed model suggests that the trimmed model also accounts reasonably well for the sample data. The examination of the residuals for the trimmed integrated model (given in Table 17)
Figure 10: Trimmed Model for Subjects Using Algorithms with Understanding

shows that part of the covariance between SC and DP is left unexplained. However, this remaining covariance constitutes only about one third of the total association between these two variables. Thus, it could be argued that the trimmed integrated model also provides a reasonable explanation of the covariances in the sample data.

A detailed analysis of the effects of each variable through the decomposition of the total associations among the variables yielded the values in Table 19. This table shows that both the direct and indirect effect of direct proportional reasoning on subsumed concepts are substantial (0.123 and 0.188
Table 19

Effects Analysis in the Integrated Model for Subjects Using Algorithms With Understanding

<table>
<thead>
<tr>
<th>Pre-determined Variables</th>
<th>Dependent Variable</th>
<th>Total Effect</th>
<th>Direct Effect</th>
<th>Indirect Effect Via</th>
<th>Spurious Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC</td>
<td>VAC</td>
<td>0.214</td>
<td>0.214</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>IP</td>
<td></td>
<td>0.300</td>
<td>0.208</td>
<td>-</td>
<td>0.012</td>
</tr>
<tr>
<td>DP</td>
<td></td>
<td>0.112</td>
<td></td>
<td>0.046 0.026 0.040</td>
<td>-</td>
</tr>
<tr>
<td>IP</td>
<td>SC</td>
<td>0.429</td>
<td>0.429</td>
<td>-</td>
<td>0.054</td>
</tr>
<tr>
<td>DP</td>
<td></td>
<td>0.311</td>
<td>0.123</td>
<td>0.188</td>
<td>-</td>
</tr>
<tr>
<td>DP</td>
<td>IP</td>
<td>0.439</td>
<td>0.439</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

respectively). However, the indirect effect through inverse proportional reasoning accounts for about 60% of the total effect (0.311).

Using the criteria of parsimony and the fact that the indirect effect accounts for a greater proportion of the covariance, the trimmed integrated model was retained. However, because the path between IP and VAC (Table 18) is relatively small, it was decided to delete this path in addition to the path between DP and SC in order to determine whether a much more over-identified model (similar to the one for the subjects using algorithms without understanding i.e. a Z-model) could be obtained which could also provide a reasonable explanation of the data for this subsample.
Analysis of the data for these subjects in terms of the Z-model gave the results presented in Table 20 and Figure 11. The result shows that all the three paths are essential to the Z-model. The chi-square test of the goodness-of-fit gave a value of 2.6655 (df = 3). This value was insignificant at the 5% level, suggesting that the Z-model may also provide a reasonable representation of the model. However, examination of the residual variance-covariance matrix (Table 21) revealed that quite a substantial proportion of the covariance between VAC and IP was unexplained. Furthermore, from Table 19, it could be seen that the direct influence of inverse proportional reasoning on volumetric analysis calculations is greater than its influence through prerequisite concepts. As such, the Z-model was rejected in favour of the original trimmed model (i.e. the non-Z-model) as being untenable.

Table 20
Parameter Estimates, Standard Errors (SE) and Critical Ratios (CR) for Subjects using Algorithms With Understanding (N = 105)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>SE</th>
<th>CR</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{43}</td>
<td>0.314</td>
<td>0.093</td>
<td>3.376*</td>
</tr>
<tr>
<td>P_{32}</td>
<td>0.483</td>
<td>0.086</td>
<td>5.616*</td>
</tr>
<tr>
<td>P_{21}</td>
<td>0.439</td>
<td>0.088</td>
<td>4.989*</td>
</tr>
</tbody>
</table>

* P < .05

Note: Model $X^2 = 2.6655$ (df = 3), $P > .05$
* Standard errors in parentheses

Figure 11: The Further Trimmed Model for Subjects Using Algorithms With Understanding

Table 21

Residual Matrix for the Next Trimmed Model

<table>
<thead>
<tr>
<th></th>
<th>VAC</th>
<th>SC</th>
<th>IP</th>
<th>DP</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAC</td>
<td>0.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP</td>
<td>0.158</td>
<td>0.000</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>DP</td>
<td>0.116</td>
<td>0.098</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Substantively, the results for the subjects using algorithms with understanding indicate that direct proportional reasoning has a strong influence on inverse proportional reasoning which in turn has a strong influence on prerequisite concepts. These results are similar to those reported for the subjects using algorithms without understanding. The results also indicate that knowledge of prerequisite concepts influences performance on volumetric analysis calculations although this influence is moderate. Furthermore, for these subjects, the ability to reason using inverse proportion may have a moderate direct influence on their performance on volumetric analysis calculations. This result is different for the one reported for the subjects using algorithms without understanding (see previous section). The implication is that for these subjects who use appropriate stoichiometric ratios in their calculations, their performance on volumetric analysis calculations may be influenced by their ability to reason using inverse proportion. It could be argued that the ability to identify the correct stoichiometric ratio in a reaction may involve the ability to balance and interpret chemical equations. Furthermore, the ability to identify how this ratio is correctly applied in calculations may involve some insight into the proportional relationships involved. As such, it seems reasonable that for subjects using the appropriate stoichiometric ratio, their performance on volumetric analysis calculations depends on inverse proportional reasoning and subsumed concepts.
The result of the model validation for these subjects also indicate that direct proportional reasoning influences knowledge of subsumed concepts mainly through its effect on inverse proportional reasoning. This is similar to the result obtained for the subjects who use algorithms without understanding (see the previous section for the discussion of this result).

Finally, relating the above results and discussions to the research hypotheses stated at the beginning of the chapter, the following conclusions can be drawn.

1. For the subjects using algorithms with understanding, even though both the proposed integrated model and the trimmed integrated model offered reasonable explanation of their sample data, the trimmed integrated model was retained as tenable on the grounds of parsimony and meaningfulness and the fact that the path between direct proportional reasoning and subsumed concepts contributed little to the explanation of their performance.

2. For the subjects using algorithms without understanding, the trimmed integrated model (or Z-model) was accepted in favour of the proposed integrated model even though both appeared to account for the observation data for these subjects. The acceptance of the trimmed integrated model was made on the grounds of parsimony, meaningfulness and the fact that the direct effect of direct proportional reasoning on subsumed concepts and that of inverse proportional reasoning on performance on volumetric analyses calculations were found to contribute little to the explanation of the sample data for these subjects.
CHAPTER VI

RESULTS AND DISCUSSION OF
DATA ON SPECIFIC STUDENT DIFFICULTIES

Introduction

In this chapter, the results for the four questions on specific student difficulties posed in the second part of the study are presented and discussed. In addition, the correlation between performance on volumetric analysis calculations and the prior number of titrations performed by the subjects is reported and discussed. The chapter concludes with a discussion of how the conceptual errors and some of the interview results bear on the validated path models for the two groups of subjects.

In reporting these results, the research question, and where appropriate the statistical hypothesis, precede the results and interpretation. The numbering of the research questions corresponds to the numbering used in Chapter I.
Conceptual Errors on Volumetric Analysis Test

To better understand some of the difficulties encountered by the students while doing the volumetric analysis calculations in the VAT, the written work displayed by the students was examined.

The specific research question addressed was:
3. What conceptual errors are made by students on the Volumetric Analysis Test?

Analysis of the steps used in solving the problems in the Volumetric Analysis Test revealed certain fundamental misconceptions held by the students. The analysis indicated that 7 students did not make any error on the Volumetric Analysis Test while the remaining 280 subjects made at least one error. Table 22 lists the conceptual difficulties that students had with volumetric analysis calculations. Only those difficulties or errors which were encountered by at least three percent of the subjects who took this test are reported in the table. The table also shows the number and percentage of subjects who made each error.

The major conceptual error made by the subjects is in assuming that in every reaction one mole of one substance will be needed to react completely with one mole of the other. It could be inferred that these subjects performed their calculations without taking into account the stoichiometric relations between the reacting substances. Thus, they used the 1:1 reacting ratio indiscriminately in their calculations. Some of these students used this ratio consistently in all
<table>
<thead>
<tr>
<th>Error No.</th>
<th>Conceptual Error</th>
<th>Number of Subjects</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Assumption of 1:1 mole ratio</td>
<td>201</td>
<td>70.0</td>
</tr>
<tr>
<td>2.</td>
<td>Concentration of stock solution different from concentration of volume used in titration</td>
<td>99</td>
<td>34.5</td>
</tr>
<tr>
<td>3.</td>
<td>Incorrect formula or formula weight</td>
<td>85</td>
<td>29.6</td>
</tr>
<tr>
<td>4.</td>
<td>Assumption of 2:1 mole ratios in problems requiring 1:1 mole ratios (especially assuming H₂SO₄ always reacts in a 1:2 ratio)</td>
<td>12</td>
<td>4.2</td>
</tr>
<tr>
<td>5.</td>
<td>Reversal of stoichiometric mole ratios</td>
<td>45</td>
<td>15.7</td>
</tr>
<tr>
<td>6.</td>
<td>Assume direct proportion between concentration and volume of solutions</td>
<td>37</td>
<td>12.9</td>
</tr>
<tr>
<td>7.</td>
<td>Equating concentration with amount (moles) of substance</td>
<td>29</td>
<td>10.1</td>
</tr>
<tr>
<td>8.</td>
<td>Calculation of moles of a substance irrespective of its purity</td>
<td>55</td>
<td>19.2</td>
</tr>
<tr>
<td>9.</td>
<td>Adding volumes of acid and base together in calculating unknown concentration or vice versa</td>
<td>17</td>
<td>5.9</td>
</tr>
<tr>
<td>10.</td>
<td>Difficulties in using mass to calculate concentration or vice versa</td>
<td>45</td>
<td>15.7</td>
</tr>
<tr>
<td>11.</td>
<td>Use of balanced chemical equations not considered in problem solution</td>
<td>173</td>
<td>60.3</td>
</tr>
</tbody>
</table>

* Total number of subjects who wrote this test = 287
problems while others used it in a few problems. The predominance of this conceptual error could be attributed to the failure on the part of the students to write balanced chemical equations or correct chemical formulas. The recognition and the use of the appropriate stoichiometric ratio in volumetric analysis calculations requires knowledge of the correctly balanced chemical equation between the reactants; this in turn requires knowledge of the formulas for the reactants. However, since Table 22 shows that quite a large number of students did not write chemical equations (60.3%) or correct formulas (29.6%), it is not surprising that the indiscriminate use of a 1:1 ratio was prevalent.

In the second conceptual error, the subjects viewed the molarity calculated from the volumes used in the reaction to be a fraction of the concentration of the original solution. This is exemplified by Pat's solution to the following problem:

If 25.0 mL of 0.5 M HCl neutralized 30.0 mL of a 250.0 mL stock solution of NaOH, what is the molarity of the 250.0 mL stock solution?

Pat's solution:

\[
\frac{0.5 \text{ mol}}{L} \times \frac{L}{1000 \text{ mL}} \times 25 \text{ mL} = 0.0125 \text{ mol HCl}
\]

\[
0.0125 \times \frac{1 \text{ mol NaOH}}{1 \text{ mol HCl}} \times \frac{L}{30} \times \frac{1000 \text{ mL}}{L} = 0.42 \frac{\text{ mol}}{L}
\]

\[
0.42 \frac{\text{ mol}}{L} \times \frac{1}{30} \times 250 \text{ mL} = 3.5 \frac{\text{ mol}}{L}
\]

From this solution one can see that Pat and other students who made similar errors did not see the concentration of the solu-
tion as remaining invariant in this problem. It seems that these students employed a direct proportional relationship between the concentration of the volume used in titration and the concentration of the stock solution. This error implied that these students may have had some misunderstanding of what a solution was since they applied a proportional relation where it was not needed. The application of this relation may be attributed to the fact that a part-whole relationship is involved here. However, this relation is not the common-sense one which suggests that the whole is greater than one of its parts and which allows the use of mathematical operations. However, the invariance of the concentration seemed to be more problematic when the subjects were asked to perform calculations than when asked to give qualitative predictions. During the interview, almost all the interview subjects indicated that the concentration of the stock solution would remain invariant when you remove a portion of it (see Table 25, Question 3).

Error number 3, incorrect formula and or formula mass, could be attributed to a number of basic misunderstandings. Firstly, ability to calculate the correct molar or formula mass of a chemical substance seemed to require knowledge of their formulas. Secondly, knowledge of the symbols for the atoms and the formulas for ionic species such as carbonate ion is needed together with a knowledge of valencies before one can write an accurate formula. It is possible that the students who made this error lacked some of this basic knowledge.
Error number 4, using a 2:1 mole ratio where a 1:1 ratio was required, was detected in about 4% of the students and was particularly evident in the problem involving the reaction of H$_2$SO$_4$ with Na$_2$CO$_3$. It seems that since, the students were already familiar with the reaction between H$_2$SO$_4$ and NaOH in which the mole ratio is 1:2, they assumed that H$_2$SO$_4$ would react with Na$_2$CO$_3$ in a 1:2 mole ratio. Once again, this could be attributed to the failure of the students to write balanced chemical equations and correct formulas. For example, some of the students were noted to assume the carbonate ion to be univalent.

Those who reversed the stoichiometric mole ratios in their calculations (error number 5), did not seem to have any problems in calculating the moles of the standard substance (i.e. the substance with known molarity and volume) used in the reaction. However, it appears that in calculating the moles of the other substance in the reaction whose concentration or volume was to be found, they became confused over whether they had to divide or multiply the moles of the standard substance by the stoichiometric ratio. That is, these subjects did not seem to recognize the nature of the relationship between the coefficients in the balanced equation and the actual moles of substances used in the reaction. They thus, probably apply an inverse relation without knowing the real relation even though they seem to know how to obtain the coefficients.

For those who made error number 6, that is assumed
direct proportion between concentration and volume of reacting solutions, it could be argued that they attempted to establish an equality between the ratios of the volumes and molarities of the acid and base involved in the reaction. However, in so doing, they assumed that the concentration varied directly with the volume of the solution. Having to decide whether there is a direct or indirect proportional relationship before doing the calculations rather than using the formula, can be looked upon as a more conceptually demanding approach and, therefore, likely to lead to more errors.

In the next conceptual error which was detected in the solutions of about 10% of the subjects (error number 7), the subjects seemed to confuse molarity with moles of substance. Part of Sid's solution illustrates this error.

25 mL of acid x .1 M = 2.5 M NaOH

It's not clear whether this difficulty was due to improper assignments of units to the variables involved as was found by Rowell and Dawson (1980) on stoichiometric calculations. If it was, then probably the use of dimensional analysis (factor labelling method) could help in removing this difficulty. However, it could be that the students have learnt certain formulas which have no proper meanings for them and hence makes it difficult for them to correctly recall and apply these algorithms.

Error number 8 made by about 19% of the subjects who calculated the moles of a substance irrespective of its purity, was detected only in solutions to the third problem
in the Volumetric Analysis Test (see Appendix A). The subjects who made this error attempted in the initial stages of their solution to calculate the number of moles of Ba(OH)$_2$. Without taking into account that it was impure, the subjects divided the given weight of the impure substance by its molar mass. These subjects did not, therefore, seem to realize that the moles of a substance in a given weight of an impure substance can be calculated only when the substance can be isolated into its pure state. Thus, they did not appear to show much understanding of when a particular memorized algorithm was applicable.

The next conceptual error (number 9), adding volumes of acid and base together in calculating the unknown concentration or vice versa, was detected in the solutions of about 6% of the subjects. It could be that these subjects did not differentiate the problems included in the Volumetric Analysis Test from problems they've done in class which involved calculating the concentration of an acid solution from a titration graph. In this latter problem, students may be asked to calculate the concentration of the remaining acid after a certain amount of base has been added. To do this, the student has to calculate the moles of acid remaining after the addition of a specified volume of base and then divide this by the total volume of solution (i.e. volume of acid + volume of added base) in order to find the concentration of the remaining acid. It seemed the students who made this error employed this method in calculating the concentration
at the stoichiometric point (which is what the problems in the Volumetric Analysis Test are about). For example, George, in solving question 2 on the test (see Appendix A) wrote:

\[ \text{Molarity of acid} = 0.50 \text{ M} \times \frac{36}{56} = 0.32 \text{ M} \]

Also, John in calculating the volume of acid in question 1 (see Appendix A) wrote:

\[ 20 \times \frac{0.02}{0.06} = 6.7 \text{ mL } H_2SO_4 \]

John seemed to extend this to situations involving the calculation of the volume. Thus, here he combined the molarities to obtain a composite molarity for the total solution. This error, therefore, illustrates an indiscriminate application of learned algorithms.

A substantial number of the students also encountered difficulties with problems requiring the calculation of the mass of a substance or the calculation of concentration from a given mass of the substance (error number 10). This error could be attributed to four basic misunderstandings detected in the subjects' solutions.

a) defining molarity as grams per millilitre,
b) multiplying grams by molar mass to obtain moles of the substance,
c) dividing molar mass by grams of substance to obtain moles, and,
d) using equilibrium constant equations.

It is evident from the above that (a), (b) and (c) again, illustrate incorrect recall and application of memorized formulas while (d) illustrates the indiscriminate application
of learned formulas. It should be noted that generally these students were able to solve problems which did not require the use of, or the calculation of, the mass of the substance. However, as soon as they confronted problems involving masses, they started applying incorrect algorithms.

As explained under the first conceptual error, conceptual error number 11 could be attributed to the inability to write correct formulas for the chemical substances involved in the reaction leading to an inability to write correct balanced equations. Some of the students were able to write the equations but could not balance them correctly.

Other errors which were made by less than 3% of the subjects and which, therefore, were not included in Table 25 included the following: dividing concentration by moles to obtain volume, and multiplying moles by volume to obtain concentration. Again, these errors illustrated that the subjects who made them probably could not recall the correct formulas required for the calculations.

It seems from the above discussions that apart from the two conceptual difficulties (error numbers 5 and 6, Table 22) which relate to the logical structure of the problems, all the other difficulties relate to a misunderstanding of the content area. Although, the above analysis seems to substantiate Herron's (1975) claim that volumetric analysis problems may be very demanding, it does not indicate that this difficulty is due to the inability of the subjects to handle inverse proportion. However, it could be argued that part of the
difficulty relates to the potential presence of both direct and inverse proportion in the same problem.

It is suggested that since students rarely conceptualize the world in chemical terms on their own (Kass, 1981), the difficulties encountered by some of the students could be attributed to the lack of application of the concepts to an everyday context in which these ideas manifest themselves, during the classroom discussions of these concepts.

Finally, relating the above discussions to the research question stated in this section, it could be concluded that the conceptual errors made by the subjects include errors related to both the logical structure of the problems (i.e. the requirement of direct and inverse proportionality) and the basic concepts such as balancing of equations and writing formulas, required by the problems.

**Manual Skills in Titration**

To identify the specific difficulties that students have when performing laboratory titrations, an analysis was done on the data from the checklist used to identify these difficulties during the titration. The specific research question addressed was:

Research Question 4:

What practical laboratory skills do subjects display in a titration experiment?

The results of the analysis of the laboratory skills used by the subjects are presented in Table 23. The table also
Table 23

Manual Skills in Titration

<table>
<thead>
<tr>
<th>Type of Skills</th>
<th>Total no. of students</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>A. Skills in Using Lab Equipment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Skills displayed in the handling and reading of burette</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Inadequate</td>
<td>17</td>
<td>36.2</td>
</tr>
<tr>
<td>b) Adequate</td>
<td>12</td>
<td>25.5</td>
</tr>
<tr>
<td>c) Superior</td>
<td>18</td>
<td>38.3</td>
</tr>
<tr>
<td>2. Skills displayed in the handling and reading of pipette</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Inadequate</td>
<td>3</td>
<td>17.6</td>
</tr>
<tr>
<td>b) Adequate</td>
<td>6</td>
<td>35.3</td>
</tr>
<tr>
<td>c) Superior</td>
<td>8</td>
<td>47.1</td>
</tr>
<tr>
<td><strong>B. Skills in Performing Lab Techniques</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Does the student need help in setting up the experiment?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>9</td>
<td>19.1</td>
</tr>
<tr>
<td>b) No</td>
<td>38</td>
<td>80.9</td>
</tr>
<tr>
<td>4. Is an indicator added to the solution before titration?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>46</td>
<td>97.9</td>
</tr>
<tr>
<td>b) No</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>5. Is caution exercised near the endpoint?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>27</td>
<td>57.4</td>
</tr>
<tr>
<td>b) No</td>
<td>20</td>
<td>42.6</td>
</tr>
<tr>
<td>6. Does the student overshoot the endpoint?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>23</td>
<td>48.9</td>
</tr>
<tr>
<td>b) No</td>
<td>24</td>
<td>51.1</td>
</tr>
<tr>
<td>7. Is the flask constantly shaken during the titration?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>39</td>
<td>83.0</td>
</tr>
<tr>
<td>b) No</td>
<td>8</td>
<td>17.0</td>
</tr>
<tr>
<td>8. Is a white background used to detect colour changes?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>18</td>
<td>38.3</td>
</tr>
<tr>
<td>b) No</td>
<td>29</td>
<td>61.7</td>
</tr>
<tr>
<td>Type of Skills</td>
<td>Total no. of students</td>
<td>Percent</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------</td>
<td>---------</td>
</tr>
<tr>
<td>9. Is the inside of the flask or beaker rinsed with distilled water during the titration?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>b) No</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>10. Is the first titration regarded as final?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>b) No</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>11. Are data recorded immediately after readings are made?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>b) No</td>
<td></td>
<td>21</td>
</tr>
<tr>
<td>12. To how many decimal places is the burette read?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) 2</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>b) 1</td>
<td></td>
<td>34</td>
</tr>
<tr>
<td>c) 0</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>13. To obtain volume of acid student uses:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Pipette</td>
<td></td>
<td>17</td>
</tr>
<tr>
<td>b) Burette</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>c) Measuring cylinder</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>14. The indicator chosen for titration is:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Phenolphthalein</td>
<td></td>
<td>31</td>
</tr>
<tr>
<td>b) Bromthymol blue</td>
<td></td>
<td>13</td>
</tr>
<tr>
<td>c) Methyl orange</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>d) All 3 indicators</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>15. Container used for titration:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Conical flask</td>
<td></td>
<td>28</td>
</tr>
<tr>
<td>b) Beaker</td>
<td></td>
<td>19</td>
</tr>
<tr>
<td>16. Is funnel used for transferring solutions into burette</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>b) No</td>
<td></td>
<td>22</td>
</tr>
</tbody>
</table>
gives the total number and the percentage of subjects demonstrating each specific skill. For example, about 38% of the subjects demonstrated accurate skills in the handling of a burette. Table 24 gives a similar information for the interview subjects when they were grouped according to the prior number of laboratory titrations performed. The three groups are those who have completed 0 to 2, 3 to 5 and 6 to 12 laboratory titrations.

The large percentage of subjects showing at least an adequate skill in the use of the burette may be ascribed to the fact that invariably in any titration conducted in the schools, a burette is used. As such, even those who have done less than five titrations seemed to know to some extent that they have to (i) rinse the burette with distilled water and the base to be used in it, (ii) read the bottom of the meniscus, and (iii) remove any trapped bubbles of air from the burette. However, it seems from Table 24, that doing more titrations may allow these ideas to become more entrenched as part of the students' laboratory techniques.

The few students selecting the pipette for use in measuring the volume of the base, imply that, in general, students may not be conversant with the operation of the pipette. It could be that they do not use it in their laboratory work. Thus they tend to use the measuring cylinder with which they are familiar even though they were told to be as accurate in their work as possible. It seems (Table 24) that those who have done less than 5 titrations tend to avoid the use of the pipette in their work.
Manual Skills Displayed by Subjects Classified According to the number of Lab Titrations performed since Grade 11*

<table>
<thead>
<tr>
<th>SKILLS</th>
<th>Number of Lab Titrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-2 (N=17)</td>
</tr>
<tr>
<td></td>
<td>3-5 (N=13)</td>
</tr>
<tr>
<td></td>
<td>6-12 (N=17)</td>
</tr>
<tr>
<td>1. Skills displayed in the handling and reading of burette</td>
<td></td>
</tr>
<tr>
<td>a) Inadequate</td>
<td>8 (47.1)</td>
</tr>
<tr>
<td>b) Adequate</td>
<td>3 (17.6)</td>
</tr>
<tr>
<td>c) Superior</td>
<td>6 (35.3)</td>
</tr>
<tr>
<td>2. Skills displayed in handling and reading of pipette</td>
<td></td>
</tr>
<tr>
<td>a) Inadequate</td>
<td>1 (5.9)</td>
</tr>
<tr>
<td>b) Adequate</td>
<td>1 (5.9)</td>
</tr>
<tr>
<td>c) Superior</td>
<td>1 (5.9)</td>
</tr>
<tr>
<td>3. Does the student need help in setting up the experiment?</td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>5 (29.4)</td>
</tr>
<tr>
<td>b) No</td>
<td>12 (70.6)</td>
</tr>
<tr>
<td>4. Is an indicator added to the solution before titration?</td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>16 (94.1)</td>
</tr>
<tr>
<td>b) No</td>
<td>1 (5.9)</td>
</tr>
<tr>
<td>5. Is caution exercised near the endpoint?</td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>10 (59.9)</td>
</tr>
<tr>
<td>b) No</td>
<td>7 (41.2)</td>
</tr>
<tr>
<td>6. Does the student overshoot the endpoint?</td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>8 (47.1)</td>
</tr>
<tr>
<td>b) No</td>
<td>9 (52.9)</td>
</tr>
<tr>
<td>7. Is the flask constantly shaken during the titration?</td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>12 (70.6)</td>
</tr>
<tr>
<td>b) No</td>
<td>5 (29.4)</td>
</tr>
</tbody>
</table>
8. Is a white background used to detect colour changes?
   a) Yes 6(35.3) 3(23.1) 9(52.9)
   b) No 11(64.7) 10(76.9) 8(47.1)

9. Is the inside of the flask or beaker rinsed with distilled water during the titration?
   a) Yes 6(35.3) 1(7.7) 4(23.5)
   b) No 11(64.7) 12(92.3) 13(17.6)

10. Is the first titration regarded as final?
    a) Yes 13(76.5) 10(76.9) 9(52.9)
    b) No 4(23.5) 3(23.1) 8(47.1)

11. Are data recorded immediately after readings are made?
    a) Yes 11(64.7) 9(69.2) 6(35.3)
    b) No 6(35.3) 4(30.8) 11(64.7)

12. To how many decimal places is the burette read?
    a) 2 0 0 1(5.9)
    b) 1 13(76.5) 9(69.2) 12(70.6)
    c) 0 4(23.5) 4(30.8) 4(23.5)

13. To obtain volume of acid, student uses
    a) Pipette 3(17.6) 3(23.1) 11(64.7)
    b) Burette 4(23.5) 0 2(11.8)
    c) Measuring cylinder 10(58.8) 10(76.9) 4(23.5)

14. The indicator chosen for titration is
    a) Phenolphthalein 9(52.9) 10(76.9) 12(70.6)
    b) Bromothymol blue 7(41.2) 3(23.1) 3(17.6)
    c) Methyl orange 1(5.9) 0 1(5.9)
    d) All 3 indicators 0 0 1(5.9)
<table>
<thead>
<tr>
<th>SKILLS</th>
<th>Number of Lab Titrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-2 (N=17)</td>
</tr>
<tr>
<td></td>
<td>3-5 (N=13)</td>
</tr>
<tr>
<td></td>
<td>6-12 (N=17)</td>
</tr>
<tr>
<td>15. Container used for titration</td>
<td></td>
</tr>
<tr>
<td>a) Conical flask</td>
<td>6(35.3)</td>
</tr>
<tr>
<td></td>
<td>8(61.5)</td>
</tr>
<tr>
<td></td>
<td>14(82.4)</td>
</tr>
<tr>
<td>b) Beaker</td>
<td>11(64.7)</td>
</tr>
<tr>
<td></td>
<td>5(38.5)</td>
</tr>
<tr>
<td></td>
<td>3(17.6)</td>
</tr>
<tr>
<td>16. Funnel used for transferring solution into buret</td>
<td></td>
</tr>
<tr>
<td>a) Yes</td>
<td>6(35.3)</td>
</tr>
<tr>
<td></td>
<td>4(30.8)</td>
</tr>
<tr>
<td></td>
<td>15(88.2)</td>
</tr>
<tr>
<td>b) No</td>
<td>11(64.7)</td>
</tr>
<tr>
<td></td>
<td>9(69.2)</td>
</tr>
<tr>
<td></td>
<td>2(11.8)</td>
</tr>
</tbody>
</table>

* Percentage of total subjects in parenthesis
This seems to be also true for the subjects when they were given the option to use certain equipment (e.g. funnel and conical flask) in their experiment. For example, the many students who chose the beaker for the titration had difficulties in swirling or stirring the solution in the beaker. Those who tried to swirl it spilled some of the solution while some of those who stirred with a glass rod could not mix the solution well. Those who spilled part of the solution while swirling the beaker did not attempt to repeat the titration run in order to obtain a more accurate endpoint. It seems as if the choice to use the beaker was dictated by the fact that this was what they had been using in their laboratory work. Here too, it seems that experience with titration (i.e. the number of prior titrations) influences the choice of the beaker or conical flask. Similarly, the choice of funnel for transferring solutions seemed to be influenced by the experience of the student with laboratory titrations.

The failure on the part of most of the subjects (68.1%) to repeat their titrations may suggest that these students may have the notion that one observation of a phenomenon may adequately represent the phenomenon.

Tables 23 and 24 also show that in performing the titration, almost all students were able to set up the experiment, added drops of the indicator to the acid in the flask before commencing the addition of base and constantly shook the titrating flask during the titration. However, almost half of the subjects overran the endpoint because they
did not exercise caution in the addition of base as they approached the endpoint and did not also use a white background to detect the colour changes in the solution. Also, about half of the subjects did not record their readings until they were asked to do so. In recording their readings, it is noteworthy that about a quarter of the subjects did not read the burette to even one decimal place. This is despite the fact that the burette is graduated in such a way that the first decimal place could be obtained accurately while the second decimal place could be estimated and the uncertainties calculated. It seemed most of the students (72.3%) avoided estimating the uncertainty involved by recording their results to only one decimal place. It could also be that this is the normal practice in the schools.

A large number of the subjects (80%) did not see the need to use the distilled water supplied in the washbottle to wash down the acid dripping on the sides of the flask or beaker into the main body of the solution. This suggests that they have probably never employed it in their titrations. Some of the teachers involved in the study indicated that the students are not allowed to use the wash bottles because they use it to squirt water on each other in the laboratory.

The choice of indicator for the titration is discussed in the next section.

Thus, it seems that above a certain degree of involvement in laboratory titrations, the subjects psychomotor skills improve while below this number, these skills are not well developed. In general it could be concluded from the
above results that the adequacy of the manipulatory skills of the subjects in the study varied. That is, while appropriate manipulative skills were shown in some areas, e.g. setting up the experiment, adding indicator to the acid before titration and shaking the flask constantly, inappropriate skills were displayed in other areas, e.g. overshooting the endpoint and not flushing the acid solution on the inside walls of the flask. It could be that this variation reflects the relative emphasés placed by teachers on these techniques.

It's been stated elsewhere (Doran, 1978) that

the precise relationship of student laboratory activities to the goals of school science courses is not clearly defined ... Each science teacher ... differs in the emphasis he gives to the student's equipment manipulation and laboratory techniques.

As such, the differing skills displayed by the subjects could be attributed to the manipulative techniques deemed by the teacher to be important. Given that one of the important objectives stated for laboratory work by chemistry teachers (Kerr, 1963; Thompson, 1975; Gunning and Johnstone, 1976) is to help students to develop appropriate laboratory skills, it is a little surprising that students in this study lack a number of important skills. However, given that these studies were conducted elsewhere and not in Canada, it may be interesting to find out the kinds of aims that chemistry teachers in British Columbia may have for practical work in the schools. It may be that one of the main aims for laboratory work is to keep the students occupied. If that's the case, then it is not surprising if the students display inadequate skills.
Concepts in Titration

To obtain a much broader view of the difficulties students have with volumetric analysis besides those identified in their calculations on VAT, students' understanding of the concepts involved in an actual lab titration situation was explored. This provided a much wider perspective on the difficulties encountered by the students.

The specific research question addressed in this section is:

Research Question 5:

What difficulties do subjects have with concepts involved in an actual titration experiment?

The results of the analysis of students' difficulties in understanding titration concepts are grouped according to whether the difficulties are mainly in the areas of pH, concentration, indicator behaviour, or scientific terminology. For each area the results from the interview questions are presented in tabular form followed by discussion.

Student Difficulties with pH

The results of the analysis of the interview questions relating to pH are given in Table 25.

The response patterns for questions 1 and 2 indicate that a large proportion of the subjects succeeded in calculating the pH of the acidic and basic solutions used in the titration by applying the mathematical definition of pH. Those
### Table 25

Questions and Response Patterns Derived From Interview Data in the Area of pH

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
</table>

**Question 1: The sodium hydroxide solution you are using in the titration is 0.1M, what will be its pH?**

1. The pH will be 13 since $\text{pH} = -\log [H^+]$ and $\text{pH} = 14 - \text{POH}$ 32 68.1
2. I don't know 5 10.6
3. The pH will be 1 3 6.4
4. The pH will be 13 since antilog of dissociation constant gives POH 1 2.1
5. pH will be 0.1 because concentration is 0.1 1 2.1
6. Others\(^a\) 5 10.6

**Question 2: If the hydrochloric acid you are using is 0.1M, what will be its pH?**

1. pH is negative logarithm of the hydrogen ion concentration so it will be 1 35 74.5
2. I don't know 6 12.8
3. pH of 1 is the highest for an acid so it will be 1 1 2.1
4. pH will be antilog of dissociation constant which is 1 1 2.1
5. pH will be 0.1 2 4.3
6. Other\(^a\) 2 4.3

\(^a\) This response pattern represents students answers which were either non-interpretable or very unusual.
Table 25 continued ...

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 5: As you're adding sodium hydroxide solution to the acid in the flask, what do you think happens to the pH of the solution in the flask?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. The pH will increase toward pH of 7</td>
<td>40</td>
<td>85.1</td>
</tr>
<tr>
<td>2. The pH will decrease</td>
<td>5</td>
<td>10.6</td>
</tr>
<tr>
<td>3. It will stay the same</td>
<td>2</td>
<td>4.3</td>
</tr>
</tbody>
</table>

| Question 6: How does the pH change at the initial stages of the titration compare to the change near the stoichiometric point for a given volume of added base? |                   |      |
| 1. The titration curve shows that it changes slowly at the beginning but shoots up near the stoichiometric point | 7                 | 14.9 |
| 2. It will be greater near the stoichiometric point because there will be smaller amount of H\(^+\) ions remaining near the stoichiometric point. | 16                | 34.0 |
| 3. It will be slower near the stoichiometric point because the moles of hydrogen ions will be less compared to the initial stages. | 6                 | 12.8 |
| 4. The pH change will be the same because a drop is a drop, it changes the same way.\(^d\) | 14                | 29.8 |
| 5. The pH will level off near the stoichiometric point                              | 1                 | 2.1  |
| 6. I don't know                                                                   | 3                 | 6.4  |

| Question 7: What will be the pH at the point when there are equal amounts of acid and base? |                   |      |
| 1. The pH will be 7                                                                | 42                | 89.4 |
| 2. The pH will be less than 7                                                      | 5                 | 10.6 |

\(^d\) One person gave this response but did not know why.

\(^c\) Of the 5 students who indicated that the pH will decrease with the addition of base, 2 gave response (2), 1 gave response (3), 1 gave response (5) and 1 gave response (6).
Table 25 continued ...

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The pH will be more than 7</td>
<td>37</td>
<td>78.7</td>
</tr>
<tr>
<td>2. The pH will be lower than 7</td>
<td>4</td>
<td>8.5</td>
</tr>
<tr>
<td>3. The pH remains at 7</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td>4. Others&lt;sup&gt;e&lt;/sup&gt;</td>
<td>3</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Question 8: When you overrun the endpoint of the titration, what will the pH be?

1. The pH will be more than 7  
2. The pH will be lower than 7  
3. The pH remains at 7  
4. Others<sup>e</sup>

Question 12: If you use acetic acid instead of HCl in the titration against NaOH, what will be the pH at the stoichiometric point?

1. It will be greater than pH 7 because acetic acid is a weak acid  
2. The pH will be 7 since 7 is the neutral point when they have reacted completely  
3. The pH will be 7 since NaOH is strong  
4. The pH will be less than 7 since acetic acid is a weak acid  
5. The pH will be below 7 because of the ratio of concentration of base to acid and the $K_d$ value  
6. pH will be zero because water has pH of zero  
7. The pH will be 4 since 4 is the stoichiometric point for NaOH + HCl  
8. The pH will be below 7 because acetic is a strong acid  
9. pH will be 1 because pH does not depend on the nature of the acid  
10. I don't know

<sup>e</sup> For example

a) pH will remain at 1  
b) pH will be 13 since it's just addition of base to H₂O  
c) pH will remain at 0
Table 25 continued ...

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 13: If ammonia is reacted with HCl in the titration, what will be the pH at the stoichiometric point?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. The pH will be 7</td>
<td>21</td>
<td>44.7</td>
</tr>
<tr>
<td>2. More than 7</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td>3. Less than 7</td>
<td>16</td>
<td>34.0</td>
</tr>
<tr>
<td>4. I don't know</td>
<td>7</td>
<td>14.9</td>
</tr>
</tbody>
</table>

who indicated that they did not know what the pH was attempted initially to recall the definition but were not successful. Others simply were confused about the definition of pH.

When asked about the effect of the added base on the pH of the acid during the titration (Question 5), almost all the students (85.1%) knew that the pH of the acid will increase. However, there were a few students who did not seem to have a clear understanding. Those who said that the pH will decrease, appeared to be confused over whether acids have pH ranges above or below the neutral pH of 7. The two students who gave the last response pattern seemed to think that the pH is a constant of a solution and hence undisturbed by the addition of other substances. These students therefore, seem to have a confused notion of pH.

A follow-up to the above was to ask the students to indicate whether there were any differences in the rate of change of pH of the acid with each drop of base at the initial
stages of the titration and any point thereafter (Question 6). A substantial number of the subjects responded that the rate of change in pH will either be the same throughout the titration or it will be slower near the endpoint of the titration. As student V explains,

"It (i.e. the rate of change in pH) will be the same; it must be because they react the same way so it doesn't matter when you added the drop, so the pH should go up steadily".

Similarly, student I explains that

"Since there are more H\(^+\) ions at the beginning, the reaction will be easier at the beginning than at the end so there will be a rapid change in pH at the beginning but it will slow down near the end."

Thus, in response pattern 4 which is exemplified by V's explanation, the students probably reason that since each drop of base has the same concentration and moles of NaOH, the change in pH should be the same throughout the titration. In response pattern 3, the students, response is diametrically opposed to response pattern 2, although the students' explanations for both patterns are the same. It may be noted however, that the students who gave response patterns 4 and 3 probably do not realize that a rapid change in pH of the solution at the stoichiometric point is necessary for the efficient operation of indicators in titration. Those who gave the first response pattern responded by drawing the titration curve but did not explain why the curve shoots up near the stoichiometric point.

Since chemistry is further removed from everyday life than the other sciences (Kass, 1981), this may suggest that these
students encounter difficulties in translating their observations into a mental picture of the molecules and the ions in solution, subsequent to any verbal explanations.

The students' responses to Question 7 show that almost all of them realized that when a strong acid reacts with a strong base in equal amounts the pH of the resulting solution will be 7. It is interesting that even though some students indicated that the pH will be lower than 7, no one said that it will be higher than 7. Those who indicated that the pH will be lower than 7 seem to be confused about how the pH operates - whether pH 7 represent acidic or basic solutions. Similarly, most of the students realized that when they overshoot the endpoint of the titration, the pH of the solution will be higher than 7 (Question 8). These students seem to realize that the addition of excess base to the final solution will increase the concentration of the OH\(^-\) ions and hence the pH. However, a few students gave a variety of responses. Here too, those who indicated that the pH will be below 7 seem to confuse the acidic and basic ranges of pH. Those who indicated that the pH will remain at 7 seem to reason that as soon as the neutral pH is reached, addition of excess base will not alter the pH. The response patterns given by the students for the titration of acetic acid against NaOH (Question 12) can be further categorised into four groups: those who indicated that the pH will be (a) above pH 7 (29.8%), (b) at pH 7 (51%), (c) below pH 7 (14.8%), and those (d) who didn't know what the pH will be (4.3%). The large fraction
of subjects who indicated that a neutral pH will be achieved appeared to equate the acetic acid-sodium hydroxide reaction with the hydrochloric acid-sodium hydroxide reaction. Some of the students who gave this response pattern indicated also that acetic acid is a weak acid but this did not deter them from saying that the pH will be 7. They did not seem to invoke the notion of hydrolyses of the acetate ion formed during the reaction. This is shown by the following response from student DD.

"The result will be the same. The pH will be 7 because it is the same as when we used NaOH and HCl; the only difference is HCl is strong acid and acetic acid is weak acid and so the difference is we only have to use less NaOH to titrate the acetic acid".

Such responses show that the students have the notion that every acid-base reaction results in a neutral solution regardless of the nature of the acid.

The subjects who indicated that the pH will be below 7 gave a wide variety of reasons none of which showed a high frequency of occurrence in the interview sample. This probably indicates the different ideas that these students have about pH. It also shows their misunderstanding of the underlying chemical concepts.

Similar response patterns were given by the students when questioned on the stoichiometric pH for the reaction between aqueous ammonia and hydrochloric acid (Question 13). This supports the notion that students assume every acid-base titration to result in a neutral solution irrespective of the relative strengths of the acid and base involved.
Student Difficulties with Concentration and its Relationship to Moles and pH

Student response patterns for the questions pertaining to the concept of concentration are presented in Table 26.

In the third question, virtually all the students seem to realize in one way or another that the concentration will remain invariant. However, the nature of their responses is noteworthy.

While the first response pattern which was given by 66% of the students is probably based on the knowledge of the preparation of solutions, the second response pattern seems to be based on the actions performed by the subject. The third response pattern which showed up in the responses of 25.5% of the students deals with the relationship among the amount of solute, the volume and the concentration of the solution. This latter response pattern may suggest that these subjects may have a better understanding of the chemistry involved than those who gave the first two response patterns.

Similar response patterns were given for the effect of decreasing volume of the solution on the moles of acid in the remaining stock solution (Question 4). Here, 55.3% attributed the decrease in the amount of acid to their actions while only a few (12.8%) related the decrease to the relationship among volume, amount of solute and concentration of solution. It is suggested that these latter students may be better able to relate their observations (i.e. decrease in volume of stock) to the relevant variables involved --
Table 26
Questions and Response Patterns Derived from Interview Data in the Area of Concentration

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 3: You took 25 mL of hydrochloric acid from the stock solution in the bottle. Do you think the 25 mL taken out from the stock solution will have any effect on the concentration of the remaining stock solution? Why?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. The concentration will be the same because concentration is the same throughout the entire solution</td>
<td>31</td>
<td>66.0</td>
</tr>
<tr>
<td>2. It will stay the same because you're not adding or taking anything</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td>3. I don't think it will change because I'm taking equal proportion of acid and water</td>
<td>12</td>
<td>25.5</td>
</tr>
<tr>
<td>4. I don't know</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Question 4: Will the volume taken from the stock solution affect the number of moles of acid in the remaining stock solution? Why?

<table>
<thead>
<tr>
<th>Reason</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. It will be less because you're taking something (moles or volume) out of the stock solution</td>
<td>26</td>
<td>55.3</td>
</tr>
<tr>
<td>2. The concentration is the same, the volume changes so the number of moles will decrease</td>
<td>6</td>
<td>12.8</td>
</tr>
<tr>
<td>3. The number of moles stays the same(^b)</td>
<td>15</td>
<td>31.9</td>
</tr>
</tbody>
</table>

Question 9: During the titration you used distilled water to flush down the acid on the sides of the flask, what effect will this water have on the concentration of the solution in the flask?

<table>
<thead>
<tr>
<th>Reason</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. It will decrease the concentration since the volume will be greater</td>
<td>26</td>
<td>55.3</td>
</tr>
</tbody>
</table>

\(^b\) Reasons given are explained in the text
Table 26 continued ...

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 9: continued ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. It will decrease because the moles will stay the same while volume will increase</td>
<td>11</td>
<td>23.4</td>
</tr>
<tr>
<td>3. Concentration will stay the same because water is neutral</td>
<td>7</td>
<td>14.9</td>
</tr>
<tr>
<td>4. Concentration will be the same but I don't know why</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>5. It will increase due to the equilibrium conditions</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>6. It will decrease because water will add more OH⁻ ions</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Question 10: How will the added water affect the number of moles of acid in the flask?

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. It will stay the same because water is neutral</td>
<td>18</td>
<td>38.3</td>
</tr>
<tr>
<td>2. The concentration will decrease but the volume will increase to make the number of moles the same</td>
<td>6</td>
<td>12.8</td>
</tr>
<tr>
<td>3. It will stay the same because you're not changing the initial number of moles</td>
<td>15</td>
<td>31.9</td>
</tr>
<tr>
<td>4. It will stay the same but I don't know why</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td>5. It will decrease because the concentration will decrease</td>
<td>4</td>
<td>8.5</td>
</tr>
<tr>
<td>6. It will decrease but I'm not sure why</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Question 11: How will the pH be affected by the added water?

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The pH will increase because the concentration will decrease</td>
<td>7</td>
<td>14.9</td>
</tr>
<tr>
<td>2. The pH will increase because water is basic</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>3. It will increase the pH since pH of water is higher</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>
**Table 26 continued ...**

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 11 continued ...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. The pH will stay the same because distilled water is neutral</td>
<td>19</td>
<td>40.4</td>
</tr>
<tr>
<td>5. The pH will stay the same because concentration of water is constant</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>6. The pH will stay the same because it is constant</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>7. The pH never changes because if it does, it will distort the calculation of the concentration</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>8. The pH will stay the same but I don't know why</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td>9. The pH will decrease because the concentration will decrease</td>
<td>10</td>
<td>21.3</td>
</tr>
<tr>
<td>10. The pH will decrease because water is neutral</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>11. I'm not sure how the pH will be affected</td>
<td>3</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Specifically, the ability to relate their observations to and manipulate the formula: molarity x volume = moles of substance. However, quite a substantial proportion of the subjects (31.9%) maintained incorrectly that the moles will remain unchanged. The reasons given by the students for this response pattern included the following: because it's the same solution or the same concentration, because moles is the same and because you're not adding any substance. These responses may be due to a lack of adequate comprehension about the distinction between the concentration and moles of substances in solution.
The response patterns under Questions 9, 10 and 11, reflect the students understanding of the effect of adding distilled water on respectively, the concentration, moles and acidity (pH) of the acid solution in the titration. In the first response pattern in Question 9, the subjects attribute the decrease resulting from the addition of water to only the increased volume - no reference is made to the amount of acid even though they may be well aware of its importance. In the second response pattern however, the subjects explicitly explain the decrease in terms of the relationships among the volume, concentration and moles of acid. Those who indicated that the concentration will stay the same probably view an increase in concentration as resulting from the addition of solutes or solutions having excess H⁺ or OH⁻ ions. As such, since water has an equal proportion of H⁺ and OH⁻ ions, they indicate that it would not have any effect on the concentration. While these students viewed water as a neutral and a non-reacting substance, at least two students thought the H⁺ and OH⁻ ions in water react with the H⁺ ions of the acid to change the concentration.

On the question of the effect of distilled water on the moles of acid used in the titration (Question 10), the response patterns of the students demonstrate that about 89% understood the relative invariance of the moles of acid in a solution (as opposed to its volume or concentration).

The few students who indicated that the amount of acid will decrease seemed unable to distinguish moles from
concentration. However, a closer look at the response patterns of the subjects who correctly answered the question shows the variety of reasons used to justify their answers. It ranges from a simple "I don't know" (Response pattern 4) to a more complex explanation embodying the relationship among the concentration, moles and volume of the solution (Response pattern 2). It would seem that those who gave response pattern 3 could be assumed to understand the inter-relationships among the concentration, volume and moles, however further probing did not seem to elicit any new information. The following protocol exemplifies this:

Student: No, it won't because you are not taking away any moles of HCl and you are not adding any.

Investigator: But you are adding water, and you mentioned that the concentration will decrease, so how will the water affect the moles of acid?

Student: The water doesn't have any effect on the moles, it only increases the volume.

The question on the effect of water on the acidity of the solution (Question 11) seemed to pose some difficulties for the subjects. With the exception of 2 students who indicated that the pH will increase because water is basic or that water has a higher pH than the acid, all the others who said that the pH will increase reasoned from the formal definition of pH as the negative logarithm of the hydrogen ion concentration. It could be argued that for these students, the formal definition of pH seems to be meaningful to them in the sense that they saw its applicability to the present problem.
Those who indicated that the pH will decrease reasoned mainly that this was the result of the decrease in concentration. Thus, they could not transfer their knowledge of the formal definition of pH to bear on this problem even though they were able to calculate the pH of the acid and the base when supplied with the molarities of the solutions. They just assumed a direct relation between concentration and pH. Thus, they seem to have difficulties in demonstrating a qualitative understanding of the mathematical relationship between concentration and pH.

The subjects who indicated that the pH will remain constant gave a variety of reasons to justify their responses (Response Patterns 3 through 7). The most common explanation was that since water contains equal amounts of $\text{OH}^-$ and $\text{H}^+$ ions it wouldn't affect the hydrogen ions already in the acid and so the pH will remain the same. It seems that, just like those students who said that the pH will decrease, these students have a rote definition of pH which becomes meaningless when it becomes necessary to apply it in a novel situation.

**Student Difficulties with Indicator Behaviour**

Student response patterns to questions related to indicator behaviour are given in Table 27.

In Question 14, with the exception of one student, all the students, in one way or the other, seem to know the function of the indicator in the titration of HCl against NaOH. Those who gave response pattern 4 indicated that if in the
<table>
<thead>
<tr>
<th>Question 14: Why is an indicator needed in this titration?</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. To indicate when the moles of base equals moles of acid</td>
<td>24</td>
<td>51.1</td>
<td></td>
</tr>
<tr>
<td>2. To indicate when the solution is neutral</td>
<td>12</td>
<td>25.5</td>
<td></td>
</tr>
<tr>
<td>3. To indicate when the solution has reached a certain pH range</td>
<td>7</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>4. To show when the solution is basic</td>
<td>3</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>5. I don't know</td>
<td>1</td>
<td>2.1</td>
<td></td>
</tr>
</tbody>
</table>

Question 15: You noted that the indicator had different colours in different mediums, how does the indicator change colour?

<table>
<thead>
<tr>
<th>Question 15: You noted that the indicator had different colours in different mediums, how does the indicator change colour?</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. The indicator is a weak acid or base with two differently coloured forms in equilibrium. The proportion of these forms in solution determines the colour of the solution</td>
<td>15</td>
<td>31.9</td>
<td></td>
</tr>
<tr>
<td>2. The indicator reacts with the $H^+$ or $OH^-$ ions to form coloured compounds</td>
<td>7</td>
<td>14.9</td>
<td></td>
</tr>
<tr>
<td>3. It's something to do with electrons in solution</td>
<td>2</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>4. I can't explain</td>
<td>21</td>
<td>44.7</td>
<td></td>
</tr>
<tr>
<td>5. Other</td>
<td>2</td>
<td>4.3</td>
<td></td>
</tr>
</tbody>
</table>

Question 16: Do you think the amount of indicator added will affect the final volume of base used in the titration? Why?

<table>
<thead>
<tr>
<th>Question 16: Do you think the amount of indicator added will affect the final volume of base used in the titration? Why?</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Yes, the indicator will react with the base to affect the volume of the base</td>
<td>10</td>
<td>21.3</td>
<td></td>
</tr>
<tr>
<td>2. It will affect the volume of base because the indicator will increase the pH of the acid</td>
<td>2</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>3. It will affect it but I don't know why</td>
<td>1</td>
<td>2.1</td>
<td></td>
</tr>
</tbody>
</table>
Table 27 continued ...

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
</table>

**Question 16 continued ...**

4. I don't think so because it only makes the colour more perceptible 11 23.4
5. No because an indicator is only there to show the endpoint 17 36.1
6. I don't think so because the indicator is a weak acid 3 16.4
7. I don't know 3 6.4

**Question 17:** Why did you choose this (particular) indicator for the titration?

<table>
<thead>
<tr>
<th>Indicator Chosen</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bromthymol blue</td>
<td>1. Because it changes between pH 6 to pH 7.6 which covers the neutral pH range 8 17.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Because it changes between pH 6-7.6 which covers pH 7 of the base 1 2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Because it gives a distinct colour 2 4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Because I'm familiar with it 2 4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenolphthalein</td>
<td>1. Because pH range falls on vertical section of the graph 2 4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Because it changes in the basic range 3 6.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Because it gives a distinct colour 4 8.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Because the acid is in the titrating flask 2 4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Because I'm familiar with it 16 34.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6. I don't know 2 4.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.7 continued ...

<table>
<thead>
<tr>
<th>Indicator Chosen</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Question 17 continued ...</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenolphthalein</td>
<td>7. Because the reaction is completed between pH 8 and 10</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>8. Because phenolphthalein is in the neutral pH range</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>Methyl orange</td>
<td>1. Because the acid is in the flask</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>2. Because it gives a distinct colour</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>All three indicators</td>
<td>1. To make sure that at least one of them indicates the endpoint</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

**Question 18:** If acetic acid is used in the titration instead of HCl which of the 3 indicators (bromothymol blue, phenolphthalein and methyl orange) will you use in the titration? Why?

<table>
<thead>
<tr>
<th>Indicator Chosen</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromthymol blue</td>
<td>1. Because pH of final solution will be around 7</td>
<td>7</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>2. Because the stoichiometric point will be around pH 6</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>3. Because I'm familiar with it</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>4. I don't know</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>Phenolphthalein</td>
<td>1. Because it changes in the basic range</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>2. Because it's pH range coincides with the stoichiometric point</td>
<td>14</td>
<td>29.8</td>
</tr>
<tr>
<td></td>
<td>3. Because pH at equivalence point is 7</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td>4. Because it is a weaker acid than acetic acid</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>5. Because it is used when acid is in the flask</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>6. Because I'm familiar with it</td>
<td>7</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>7. I don't know</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>
Table 27 continued ...

<table>
<thead>
<tr>
<th>Indicator Chosen</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl orange</td>
<td>1. Because acetic acid is a weak acid</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>2. Because it is used when the acid is in the flask</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>3. I don't know</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>None</td>
<td>1. I don't know</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td>Others</td>
<td>1. I'll use both methyl orange and bromthymol blue (no reason)</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Question 19: If ammonia is used in the titration which indicator out of the three will you choose?

1. Bromothymol blue 9 19.1
2. Phenolphthalein 21 44.7
3. Methyl orange 13 27.7
4. I don't know 4 8.5

Question 20: Do you think you could have used any of the other indicators in this titration? Why?

<table>
<thead>
<tr>
<th>Indicator not used in Titration</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl orange</td>
<td>1. Could be used because pH range will fall on vertical section of graph</td>
<td>2</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>2. Could be used because HCl is stronger acid than methyl orange</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>3. Could be used because it's an indicator</td>
<td>4</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Table 27 continued ...

<table>
<thead>
<tr>
<th>Indicator not used in Titration</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Methyl orange</strong></td>
<td>4. Could be used because choice of indicator depends on whether you're finding the concentration of the acid or base in the flask</td>
<td>3</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>5. No because pH of methyl orange is far too low</td>
<td>27</td>
<td>60.0</td>
</tr>
<tr>
<td></td>
<td>6. No because pH of methyl orange doesn't span the acid and basic range</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>7. No, I'm not familiar with methyl orange</td>
<td>5</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>8. No, but I don't know why</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>9. I don't know</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Phenolphthalein</strong></td>
<td>1. I can't use it because it's pH does not span the acidic and basic range</td>
<td>1</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>2. I can't because the colour is not distinct</td>
<td>1</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>3. Can't because pH is high</td>
<td>7</td>
<td>46.7</td>
</tr>
<tr>
<td></td>
<td>4. Could be used because its range will fall on vertical section of graph</td>
<td>1</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>5. Could be used because choice of indicator depends on whether acid or base is in the flask</td>
<td>1</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>6. Could use it because pH is close enough to 7</td>
<td>2</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td>7. I don't know</td>
<td>2</td>
<td>13.3</td>
</tr>
<tr>
<td><strong>Bromthymol blue</strong></td>
<td>1. Could be used because its pH range will fall on vertical section of graph</td>
<td>3</td>
<td>9.1</td>
</tr>
</tbody>
</table>
Table 27 continued ...

<table>
<thead>
<tr>
<th>Indicator not used in Titration</th>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 20 continued ...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bromothymol 2. Could have used it because pH goes over 7</td>
<td>4</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>3. Could have used it because it's an indicator</td>
<td>4</td>
<td>12.1</td>
<td></td>
</tr>
<tr>
<td>4. Could have used it since choice of indicator depends on whether acid or base in the flask</td>
<td>2</td>
<td>6.1</td>
<td></td>
</tr>
<tr>
<td>5. Could be used because HCl is stronger than bromothymol blue</td>
<td>1</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>6. Could have used it because pH range is around stoichiometric point</td>
<td>5</td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>7. No, because I'm not familiar with it</td>
<td>3</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>8. Can't because pH range is low</td>
<td>9</td>
<td>27.3</td>
<td></td>
</tr>
<tr>
<td>9. Can't because pH is near neutral range</td>
<td>1</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>10. I don't know</td>
<td>1</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

titration a base is being added from the burette to the acid, then an indicator should be chosen which changes in the basic pH range. These students, therefore, do not seem to have a correct conception of the function of an indicator. With regard to those who indicated that the final solution will be neutral, examination of their responses to follow-up questions relating to the pH at the stoichiometric point for the reactions between HCl and NaOH, NH₃ and HCl, and acetic acid
and NaOH seem to indicate generally that they regard every acid-base reaction to result in a neutral solution irrespective of the nature of the reactants. Despite this confusion it could be inferred that the subjects generally understand why indicators are used in acid-base reactions involving strong acids and strong bases.

However, as the responses on Question 15 shows, quite a large percentage of the subjects either did not know how the indicator used in the titration changed colour or they conjured up some other explanations. In the first response pattern, the students realize that the colour of the indicator is determined by the proportion of the undissociated form and the dissociated form (or conjugate acid or base). In the second response pattern, students seem to have the notion that the hydrogen ions in the solution complexes with the indicator to form coloured compounds. In the third response pattern reference is made to the transfer of electrons or the effect of light on electrons in solution as the cause of the colour changes.

When asked about the effect of using a large volume of the indicator (Question 16), only about a quarter of the subjects indicated that the indicator will affect the titration results. These students seem to realize that since the indicator is a weak acid or base it will react to increase (if it's a weak acid) or decrease (if it's a weak base) the volume of the base.

The large number of students who indicated that the
increased volume of the indicator wouldn't affect the titration results, reasoned in two main ways. One group (23.4%) reasoned that the indicator only makes the colour deeper and hence more perceptible. Thus, these students appealed only to the sense data (their observations) without trying to understand the possible underlying chemical processes. A second group (36.1%) reasoned that the indicator is only used to indicate when the reaction is complete and as such shouldn't affect the volume of added base. These students also seem to address themselves basically to the function of the indicator. Some of these students indicated by their responses that the indicator is a neutral substance or, even if it is an acid, it's so weak that it doesn't have sufficient hydrogen ions to make a difference.

It could be stated in general that although quite a number of students realized that an indicator is a weak acid, they did not realize that if used in large amounts it would affect the volume of base needed in the titration. This is despite the fact that most know that weak acids like acetic acid react with sodium hydroxide. The inadequate conceptions that the students have of the behaviour of acid-base indicators in titration can also be noticed in their selection of indicators for the titration of HCl against NaOH and the reasoning behind their choice (Question 17). It's notable that 66.1% of the interview subjects selected phenolphthalein while 27.7% used bromthymol blue. Only 4.2% chose methyl orange for the titration. Looking back at the response
patterns for Question 7, one would have expected that most of the students would select bromthymol blue for the task. However, this wasn't the case. It is interesting also, that most of the students explained their choices in terms of their experiences (familiarity) with the indicators. Of the subjects who chose phenolphthalein 71% indicated in some way that their selection was based on their laboratory experiences. That is, either they are familiar with it, they know it's used when acid is put in the titrating flask or because it gives a distinct colouration. These students did not relate their choice to any chemical criteria. Only a few (4.3%) indicated that even though its pH range was beyond pH7, they could still use it because of the wide range of pH change near the stoichiometric point of the reaction.

Of those who selected bromthymol blue as an indicator, 31% seemed to indicate that their selection was based on their laboratory experiences. The rest explained their choices by relating the pH range of the indicator to the pH at the stoichiometric point for the reaction between HCl and NaOH. The two subjects who chose methyl orange also reasoned in terms of their laboratory experiences.

Thus, in all about 64% of the total interview sample used particular indicators for the titration of HCl with NaOH because of their experiences with them. These students, used the indicators without showing an understanding of why they are used (i.e. without appealing to the chemical processes involved). The students did not realize that the sharp increase
in pH near the stoichiometric point makes it possible for any of the three indicators to be used in the titration of strong acids with strong bases (Toon and Ellis, 1973). This may be reflected in their lack of understanding of how the pH of the acid changes during titration.

The above trend in the choice of indicators noted for the titration of HCl with NaOH can also be found to some extent in the choices made by the students in the titration of acetic acid against sodium hydroxide (Question 18) and the titration of ammonia against sodium hydroxide (Question 19). With the NaOH - acetic acid reaction, there seems to be a slight shift both in the proportion selecting a particular indicator and the reasons offered by the students to explain their choice. Instead of relating it to their laboratory experiences, half of the students who made the correct choice (i.e. chose phenolphthalein) explained their selection by relating the pH range of the indicator to the pH at the stoichiometric point for the reaction between acetic acid and sodium hydroxide. These students alluded to the strength of the acid and base and the ensuing hydrolysis to explain the pH of the final solution. However, still an appreciable proportion of those who chose phenolphthalein (33%) indicated that their choice was based on their laboratory experiences. In fact, those who said they were familiar with phenolphthalein indicated that they had not used the other indicators to any appreciable extent so they just stuck to what they've been using in the lab. As one student explained: "I will probably
use the same indicator, phenolphthalein. This is what I used in class". Also those who indicated that phenolphthalein is used when the acid used in the titration is placed in the flask instead of the burette, seem to think that if the acid is in the flask, then it suggests that one wants a basic solution whereas the opposite will mean one wants an acidic solution as the final solution. That is, the purpose of titration is to obtain an acidic or basic solution. These students therefore applied irrelevant variables like the position of the acid in the titration to explain their choice instead of looking at variables like the strength of the reactants, the hydrolysis resulting from their reaction and the probable acidity of the product of hydrolysis.

Those who made an incorrect choice by selecting bromthymol blue mostly reasoned that the pH at the stoichiometric point will be 7 even though some of them knew that acetic acid was a weak acid. The same trend was noted in the titration of ammonia against hydrochloric acid (Question 19).

Those who chose methyl orange reasoned that since acetic acid is a weak acid and sodium hydroxide is a strong base, the equilibrium of the hydrolysis will shift toward the acid side of the pH scale. This shows an inadequate grasp of the concept of hydrolysis.

The lack of adequate knowledge about the selection of indicators for titration was also noted when the students were asked to indicate if the other two indicators not used in the titration of HCl against NaOH could have been used in
the titration (Question 20). About 75.6% of those who did not select methyl orange indicated that they couldn't have used it while only 22.2% stated that they could have used it. Those who said that it can't be used, explained mainly by saying that the pH of the methyl orange was far lower than the pH at the stoichiometric point or they had not used it in their lab work. Although some of these students seemed to realize the importance of the stoichiometric point, they failed to recognize the wide range of pH change near the stoichiometric point. The main reasons offered by those who indicated that it could be used were that methyl orange was an indicator and the choice of indicator depends on whether acid or base is in the burette. That is, these subjects appealed to their lab experiences for an explanation.

About 60% of those who did not select phenolphthalein stated that they couldn't have used it in the titration and their major reason was that the pH range of phenolphthalein was high. These students, also did not recognize the wide range of pH change at the stoichiometric point for strong acid-strong base reactions. A similar argument can be used for the 26.7% who indicated that they could have used phenolphthalein by reasoning that its pH range was close to pH 7 or that the acid was in the flask.

With regard to those who did not select bromthymol blue, 39.4% indicated that it can't be used in the titration because its pH range is low or because they haven't used it often in the lab. However, 57.6% stated that they could have
used it in the titration. These students reasoned by saying that its pH range was around that of the stoichiometric point, that it's an indicator, or that the pH range is higher than 7. Only a few students (9.1%) indicated that it could be used because of the wide range of pH change near the stoichiometric point - from about pH 3.0 to pH 10, even though many subjects drew titration curves to explain the changes in pH during titration (see Question 6).

The picture portrayed by the response patterns on Question 20 is that most students blindly perform titrations without showing adequate understanding of why they use certain indicators. There also seems to be an inadequate application or transfer of knowledge learnt in other situations (e.g. titration curves) to the task given to them.

In general, it seems that an adequate understanding of indicator behaviour, as it is reflected in Questions 14, 15, 16, 17, 18, 19 and 20, will require an understanding of:

a) the nature of indicators (i.e. what kind of substances they are),

b) the relationship between the pH at stoichiometric point for the reaction and the pH range of the indicator,

c) and the changes in pH during titration (i.e. a clear understanding of titration curves). The knowledge of the pH at the stoichiometric point of the reaction will in turn require knowledge of:

i) the nature of the acid and base involved in the titration - i.e. whether they are strong or weak, and
ii) whether their salt undergoes hydrolysis.

Even though all these concepts have been taught in class, the students often did not seem to apply them in their explanations. It's possible that in teaching volumetric analysis, no attempt is made to integrate these concepts into a coherent whole so as to present a total picture to the students. Maybe if this integration is emphasized especially during lab activities, it may go a long way to improve the students' understanding.

**Student Difficulties with Scientific Terminology**

The response patterns from the interview data relating to student difficulties with scientific terminology are presented in Table 28.

The two questions in Table 28 (Questions 21 and 22) attempted to examine the students understanding of certain scientific terms used to describe aspects of the acid-base titration. The two terminologies examined were indicator endpoint and stoichiometric point. In the first response pattern in Question 21, the students correctly related the endpoint to the colour changes occurring in the indicator. In the second response pattern an appreciable number of students (23.4%) assumed that the endpoint always occurs at pH of 7 when the solution is neutral. That is, they see the endpoint as the neutralization point. In the third response pattern, the students defined the endpoint just like the stoichiometric point. Although the endpoint may not necessarily coincide with the stoichiometric point, when the students were ques-
Table 28

Questions and Response Patterns Derived from Interview Data in the Area of Scientific Terminology

<table>
<thead>
<tr>
<th>Response Pattern</th>
<th>Number of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Question 21: What is the endpoint in a titration?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. When the colour of the indicator changes</td>
<td>13</td>
<td>27.7</td>
</tr>
<tr>
<td>2. When the solution is neutral</td>
<td>11</td>
<td>23.4</td>
</tr>
<tr>
<td>3. When there are equal amounts of OH(^-) and H(^+) ions</td>
<td>12</td>
<td>25.5</td>
</tr>
<tr>
<td>4. When concentration of both acid and base are equal</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>5. I don't know</td>
<td>10</td>
<td>21.3</td>
</tr>
<tr>
<td>Question 22: What is the stoichiometric point or equivalence point in titration.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. When the moles of OH(^-) and H(^+) ions are equal</td>
<td>23</td>
<td>48.9</td>
</tr>
<tr>
<td>2. When the concentration of H(^+) and OH(^-) ions are equal</td>
<td>6</td>
<td>12.8</td>
</tr>
<tr>
<td>3. When the solution is neutral</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td>4. The volume of the acid is equal to volume of base</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td>5. I don't know</td>
<td>15</td>
<td>31.9</td>
</tr>
</tbody>
</table>

tioned further on the relationship between the two terms, they maintained that they were the same. Thus, no attempt was made by the students to distinguish between the stoichiometric point of the reaction from the indicator endpoint. The responses further depict that a significant number of students did not know what endpoint meant.
Similar response patterns were noted for the stoichiometric point (Question 22). However, here, quite a large number of the subjects (48.9%) seemed to show an understanding of what stoichiometric point or equivalence point meant. No attempt was made by the investigator to see if the student understood both of these terms. The students were required to explain any one of the terms that they knew. As the third response pattern shows, only a few students related the stoichiometric point to neutralization. In the second response pattern, stoichiometric point is described in terms of the concentrations of acid and base instead of the moles of acid and base. These students did not seem to differentiate between moles and concentrations. A similar situation occurred (see Question 10) when students were asked to indicate the effect of adding distilled water to the acid on the moles of acid in the titration flask. The fifth response pattern indicates that quite a large number of subjects (31.9%) did not know what stoichiometric or equivalence point meant although most of these subjects used one of these terms in their responses.

In general, it could be stated that even though the students employed the chemical terms, endpoint and stoichiometric point in their descriptions, they seemed to have an inadequate understanding of these terms. This supports the observation made by Dahlgren and Marton (1978) that increased language sophistication by a subject is not necessarily followed by a greater depth of understanding of the terms used. The inadequate understanding of the terms could be
ascribed to the possibility that, in teaching volumetric analysis, teachers are normally satisfied when they find out the students can use the chemical terms introduced by them. They therefore, fail to go a step further to check on what the terms mean to the students. The possibility also exists that these terms may be used unconsciously by the teacher; the students pick them up and start using them as part of their own language.

It seems that in titration experiments in the schools, much more emphasis is placed on the student being able to obtain the volumes for subsequent use in their calculations than understanding the processes and observations involved. In addition, different emphasis are placed on the manipulation techniques required to obtain accurate volumes. No attempt is made, however, to see whether the subjects understand the processes occurring in the experiment. Also insufficient attention seemed to be given to how the students relate the various concepts such as pH, concentration, moles and indicator behaviour which they have learned in different lessons. It seemed that a much better understanding could be achieved if attempts are made to question the students as they are doing experiments so as to understand the notions which they bring into the situation.

Also, the difficulty which the students seemed to have might be partly due to the particular nature of chemistry as distinct from physics or biology (Kass, 1981; Gunning and Johnstone, 1976). This is the requirement to translate the
facts which the students observe (e.g. the indicator changes colour) into a mental picture (that the indicator contains ions surrounded by water molecules; that these particles have different colours) or into a chemical formula or equation, before any meaningful conclusions can be drawn. This factor, that the conclusions, theories and explanations in chemistry are two steps removed from reality is taken for granted by chemistry teachers. Also, taken for granted is the fact that chemical knowledge is generated mainly in the classroom through the teachers' interpretation since there's very little chemical experience which the students have prior to formal instruction. It is possible that if cognisance is taken of these limitations, much can be done to help the students in their struggle to understand nature in chemical terms.

Approaches Used in the Computation of Solution Concentration

The latter part of the interview required the students to determine the concentration of hydrochloric acid using the data obtained during the experiment. In doing this, the students were encouraged to verbalize their calculations so as to determine the method of approach used. Subsequent to this, the students were asked to predict the concentration of the acid in three different situations in order to gain a more detailed understanding of difficulties encountered in using the different approaches.

The specific research question addressed in this part of the study is:
Research Question 6:
What are the different approaches used by the subjects in solving a volumetric analysis problem?

The analyses of the transcribed verbal protocols together with the written calculations, indicated that basically only two approaches with their variants, as was found in the pilot study, were employed by the subjects to solve the problem. These two approaches referred to as the Formula Approach and the Proportional Approach are shown in Tables 29 and 30.

In the Formula Approach, the student employs a formula given in his text to solve the problem. Such formulas may be: moles of base = molarity of base x volume of solution of base, or molarity of base x volume of base = molarity of acid x volume of acid solution. The application of the first one is referred to as the basic form of the Formula Approach, F(B), while the use of the latter is termed the Variant of the basic form of the Formula Approach, F(V), in that it derives from a combination of steps in the basic form. The variant form is represented in Table 30. These two forms of the Formula Approach are represented in flow diagrams in Figures 12 and 13.

In the Proportional Approach, the student uses a ratio or proportional relation to obtain the moles of base or the concentration of the acid without explicitly employing any of the formulas normally represented in their text. For
### Table 29
Approaches to Problem Solving Employed by Subjects

#### Proportional Approach - Basic

1. Record data from experiment
2. Write balanced equation
3. Determine mole ratio between base and acid.
   For NaOH and HCl, it is 1:1
4. Find moles of base since concentration is known using proportion
5. Determine moles of acid from the moles of base and the stoichiometry using proportion
6. Compute concentration of acid using the proportional relation between concentration and volume.

#### Formula Approach - Basic *

1. Record data from experiment
2. Write balanced equation
3. Determine mole ratio between base and acid.
   For NaOH and HCl, it is 1:1
4. Apply formula: \( \text{Moles}_B = M_B V_B \)
5. Use mole ratio to compute moles of acid.
6. Apply the formula: \( \text{Moles}_A = M_A V_A \) or \( M_A = \frac{\text{Moles}_A}{V_A} \)
7. Substitute values
8. Compute concentration of acid.

* \( M_B, V_B \) and \( M_A, V_A \) stands for the molarities and volumes of the base and acid, respectively.
Table 30

Approaches to Problem Solving Employed by Subjects

Proportional Approach - Variant

1. Record data from experiment
2. Write balanced equation
3. Determine mole ratio between base and acid
4. Use the proportional relation:

\[
\frac{V_B}{V_A} = \frac{M_A}{M_B}
\]

5. Apply the stoichiometric mole ratio to the above relation to obtain molarity of acid.

Formula Approach - Variant

1. Record data from experiment
2. Write balanced equation
3. Determine mole ratio between base and acid
4. Apply the formula: \( M_A V_A = M_B V_B \) and mole ratio
5. Substitute values
6. Compute the concentration of acid.
Balanced Equation

Volumes from titration and conc. of base given

Stoichiometric Ratio eg. 1:1

Apply formula: Moles of base = MV

Compute moles of acid

Apply Formula:
\[ M = \frac{\text{moles}}{\text{litre}} \]

Substitute values

Compute conc. of acid

Figure 12: The Formula Approach to Problem Solution - the Basic

*The variant approach combines steps 4, 5 and 6 into one step.
Figure 13: The Formula Approach to Problem Solution - the variant.
example, student C reasoned that,

"...... one litre of the base contains 0.1 moles; then since I used 20 millilitres of base, the millimoles of base used in the titration is 2.0 ..."

This method of problem solution is what is referred to as the basic form of the Proportional Approach, P(B). The variant of this approach, P(V) involves establishing an inverse proportionality between the volumes and concentrations of the acid and base used in the titration. As in the case of the variant of the Formula Approach, the variant of the Proportional Approach derives from a combination of steps in the basic form. The variant form of the Proportional Approach is also represented in Table 30. This approach is conceptually more difficult than the Formula Approach where an algorithm is applied. A diagramatic representation of the two forms of the Proportional Approach can be seen in Figures 14 and 15.

In addition to the four basic approaches, some students employed other approaches in their attempts to solve the problem. However, these students were not successful. Some of the procedures used by these students include defining the quotient of the volume of the acid to the molarity of the base as the molarity of the HCl. Another subject wrote the balanced equation for the reaction between HCl and NaOH and then proceeded to determine the concentration of the HCl by dividing the molarity of NaCl by the molarity of NaOH. These incorrect procedures are referred to as the NC Approach i.e. not clearly defined approach.
The variant of this basic approach involves the combination of 4 and 5 into a single step by utilizing the inverse equality between the ratio of the volumes of base and acid used in the titration and the ratio of their concentrations, i.e.

\[
\frac{V_B}{V_A} = \frac{M_A}{M_B}
\]
1. Volumes from Titration and Conc. of base given

2. Balanced Equation

3. Stoichiometric Ratio e.g. 1:1

4. Using the Proportional relationship between the concentrations and volumes of acid and base. e.g.

\[
\frac{V_B}{V_A} = \frac{M_A}{M_B}
\]

5. Compute Conc. of acid from above relation

Figure 15: The Proportional Approach to Problem Solution - Variant
The distribution of the interview sample with respect to these approaches is presented in Table 31. The Table also shows the number of students who were successful in computing the molarity of HCl from their data. The distribution of these subjects according to their achievement on the VAT is presented in Table 32.

As Table 32 shows, students in the high and medium achievement groups did not use the variant form of the Proportional Approach, \( P(V) \), while 26% of the students in the low achievement group used it.

The results as presented in Table 31 shows that only two of the twenty-two students who employed the basic form of the Formula Approach, \( F(B) \), obtained incorrect solutions. The errors made by these two students were that they interchanged the volumes of acid and base and also mixed up millimoles with moles in their calculations. It is suggested that since these errors relate mainly to the use of the data, they may be easily remedied if the student is made to pay more attention to the values for the variables in the problem.

The student who failed to obtain a correct solution when using the \( F(V) \) approach, made an error by incorporating the molar mass of hydrochloric acid into the formula thereby resulting in an incorrect solution. Clearly, this student did not seem to understand the formula he was using. With those using the Proportional Approach one student who employed the basic approach, \( P(B) \) obtained an incorrect result when he mixed up millimoles with moles in his calculation. However,
Table 31
Distribution of Students According to Approach

<table>
<thead>
<tr>
<th>Approach*</th>
<th>Total no. of S.S.</th>
<th>No. with Correct Soln.</th>
<th>Steps Missing</th>
<th>Balanced Equation</th>
<th>Stoichiometric Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>F(B)</td>
<td>22</td>
<td>20</td>
<td>11</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>F(V)</td>
<td>12</td>
<td>11</td>
<td>9</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>P(B)</td>
<td>6</td>
<td>5</td>
<td>3</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>P(V)</td>
<td>4</td>
<td>1</td>
<td>4</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>NC</td>
<td>3</td>
<td>0</td>
<td>2</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

* F(B) = Formula Approach - Basic  
  \[ M \times V = \text{moles} \]

F(V) = Formula Approach - Variant  
\[ M_1 \times V_1 = M_2 \times V_2 \]

P(B) = Proportional Approach - Basic  
\[ 1000 \text{ ml} = .1 \text{ M} \]  
\[ \therefore 17.5 \text{ ml} = ? \]

P(V) = Proportional Approach - Variant  
\[ \frac{V_a}{V_b} = \frac{M_b}{M_a} \]

NC = Incorrect Approaches which are not clearly defined  
e.g.

1)  
\[ \frac{\text{Volume of acid}}{\text{Conc. of base}} = \text{Molarity of acid} \]

2)  
\[ \text{Conc. HCl} = \frac{\text{Conc. NaCl}}{\text{Conc. NaOH}} \]
Table 32

Distribution of Interview Sample by Strategy and Achievement Group.  N = 47

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Achievement Group</th>
<th></th>
<th></th>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(B)</td>
<td>10</td>
<td>9</td>
<td>3</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>F(V)</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>P(B)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>P(V)</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>NC</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>16</td>
<td>16</td>
<td>15</td>
<td></td>
<td>47</td>
</tr>
</tbody>
</table>

\[ \chi^2 = 14.157 \text{ (df = 8)} \quad .1 < P > .05 \text{ n.s.} \]

three of the students using the variant approach, P(V), obtained incorrect solutions when they assumed a direct proportionality relation between the concentration and volume of the solutions. As suggested earlier (in this chapter), this difficulty may be due to the fact that both direct and inverse proportional relations are involved in this problem. It is possible, therefore, that even though the students may be aware of their joint presence, they may not know which relation applies to which set of variables. Alternatively, they may know from the nature of the problem that a relation exists, but then they proceed to assume this relation to be one of direct proportion. It is further suggested that this approach, P(V), may be conceptually more difficult than the Formula
Approaches where a memorized algorithm is applied. This may account for the few students using this approach.

The students who used the NC Approach seemed to employ incorrect and inappropriate formulas in their solutions. For example, one appeared to confuse volumetric analysis calculations with calculations in reaction kinetics involving equilibrium constants. It seems therefore that, for these students who happen to fall in the low achievement group (Table 32), some of the formulas they have learnt did not make much sense to them in that they are either recalled incorrectly or they fail to see when they are applicable.

In this initial problem which involved a 1:1 mole ratio between NaOH and HCl, the balancing of the chemical equations for the reactants and the deduction of the mole ratio from it did not seem to relate to the correct solutions of the subjects. As Table 31 shows, eleven of the students who used the F(B) approach did not write balanced equations while nine of those using the F(V) approach did not write equations. Also five of those who used the F(V) approach did not indicate the mole relationship between the acid and the base. When queried about the necessity for writing balanced chemical equations in such stoichiometric problems, almost all the subjects who did not write equations indicated that they knew the reaction between HCl and NaOH so well that they found it a waste of time to write it down. Most of them however, indicated that with more complex reactions they would write balanced equations in order to obtain the correct mole ratios. The rest main-
tained that they could obtain the mole ratios just by inspecting the formulas to see how many hydrogen or hydroxide ions are present.

The finding (see Table 32) that subjects in the high and medium achievement groups employed mainly the Formula Approach, while those in the low achievement group used both the Formula and Proportional Approaches in about equal proportion is both interesting and important. Considering that the P(V) approach is conceptually more demanding than the Formula Approaches one would have expected the low achievement group to employ the Formula Approach mainly and the high achievement group to employ the P(V) approach. However, this was not the case. It could be that the subjects in the high achievement group attempted to find the easiest possible route to the solution of the problems. On the other hand, the low achievement group (who in the first place, may not have a coherent understanding of the calculations involved) assume a direct relationship between the variables as soon as they can identify from the problem that some kind of relationship exists between them. This probably explains the large number of subjects in the low achievement group obtaining incorrect solutions with this approach. The possibility also exist that the approaches used reflect the approaches normally used in their class work.

It would probably seem that some relationship might exist between the approach used and the achievement level. However, a chi-square test of independence seems to indicate
that there is no significant relationship between the type of approach used and the achievement level on the Volumetric Analysis Test (see Table 3.2). A similar insignificant relationship was found when the formula approaches were combined and the proportional approaches were also combined.

The finding that essentially two basic approaches - the Formula and the Proportional Approaches - were used by the students probably reflects the heavy emphasis on these two approaches by individual chemistry teachers. However, the fact that most students used the Formula Approach may further reflect the emphasis given to this approach in many classrooms. In any case, it cannot be said that one approach is preferable to the other. The important factor is that those who employ a particular approach understand why those relations inherent in the approach they are using exist (i.e. the meaningfulness of the approach to them). It is possible, however, that with an insight into the relations in any particular approach, the student can probably discover other alternative routes to the solution of the same problem.

Predictions of Concentration

In this part of the study, after calculating the molarity of HCl from their data, the subjects were asked to use the same data to predict the molarity of the acid when three different reactions were considered. Subjects who did not show their calculations were asked to do so after they've
made their predictions. Essentially the subjects used the same approach employed in the initial task to solve these problems. The detailed predictions of each student on the three questions posed in this part of the study and the type of solutions obtained in the initial problem involving a 1:1 mole ratio are listed in Appendix M. Table 33 presents the distribution of the subjects according to the approach used and the number of correct predictions.

Table 33

Distribution of Subjects According to Approach and number of Correct Responses on the Three Prediction Questions

<table>
<thead>
<tr>
<th>Approach</th>
<th>3 Correct</th>
<th>2 Correct</th>
<th>1 Correct</th>
<th>None</th>
</tr>
</thead>
<tbody>
<tr>
<td>F(B)</td>
<td>8</td>
<td>4</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>F(V)</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>P(B)</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>P(V)</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>NC</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 16 gives a diagrammatic representation of the predictions made by the subjects using the different approaches. The words in the boxes in columns three through five identify the type of prediction made by the subject. For example, in the case of the reaction between NaOH and H₂SO₄, the subject may predict that the molarity of the acid is half, the same or
Figure 16: Diagramatic Representation of the Predictions of Subjects using the Different Approaches

LEGEND: See next page
LEGEND:
The numbers in boxes refer to the total number of subjects using the approach in question.
The numbers on top of the arrows refer to the number of subjects giving a particular response (to the different problems).
The curved arrow designate changes in responses by some subjects with the direction of the arrow showing the final response.
* These students obtained correct predictions in some cases but could not calculate the concentrations from the experimental results.

twice as much as the molarity calculated for the initial reaction between HCl and NaOH. The 'Other' category refers to responses like 'I don't know' or an incorrect calculation which was far away from being the same, half or double the initial concentration. The numbers in the boxes in column two represent the number of subjects using a particular approach. For example, 22 subjects used the basic form of the Formula Approach. The numbers on the straight lines with arrows show the number of subjects making a particular prediction. For example, 7 students out of the 22 using the F(B) approach predicted that the molarity of the acid in a situation where two moles of acid reacts with one mole of base is half the molarity calculated for HCl in the initial reaction. The curved arrows indicate changes in the responses of the subjects with the direction of the arrow showing the final responses. Thus, one subject using the P(B) approach changed his response from half to twice as much as the
initial molarity of the HCl. In discussions based on this diagram, the direction of the arrow is assumed to indicate the path of the subject's predictions on the three problem situations. From the diagram, it can be seen that the most frequent path taken by the subjects who used the F(B) approach as a group in their predictions is Twice $\rightarrow$ Half $\rightarrow$ Twice, which is the correct solution. However, quite a substantial number used the paths: Half $\rightarrow$ Same $\rightarrow$ Same; Half $\rightarrow$ Half $\rightarrow$ Same; and Half $\rightarrow$ Half $\rightarrow$ Twice.

For those who used the F(V) approach most of them used the path: Half $\rightarrow$ Half $\rightarrow$ Same, although quite a substantial number used the correct path: Twice $\rightarrow$ Half $\rightarrow$ Twice.

With those who used the P(B) approach most of them used the predictive path: Twice $\rightarrow$ Half $\rightarrow$ Twice. However, for those using the P(V) approach, there is no clear pattern. The path seems to go from Half $\rightarrow$ Half (for the 2 Acid: 1 Base to NaOH: $H_2SO_4$ respectively) while different predictions are made for the Na$_2$CO$_3$: HCl situation. Those using the NC approach also employed different predictive paths.

Table 34 gives the predictions made by the subjects and the explanations offered for their predictions. Examination of a previous table (Table 31) shows that about 78.7% of the subjects involved in the interview obtained a correct solution to the initial problem involving the reaction between HCl and NaOH. However, when asked to predict the concentration of the acid in the three problem situations...
<table>
<thead>
<tr>
<th>Questions</th>
<th>Students Predictions</th>
<th>Explanations</th>
<th>No. of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. If the acid reacted with the base in a mole ratio of 2:1 respectively, what will be the concentration of the acid?</td>
<td>Twice as much</td>
<td>Since the acid will have twice as much moles as the base</td>
<td>25</td>
<td>53.2</td>
</tr>
<tr>
<td></td>
<td>Half as much</td>
<td>There are 2 moles of acid to 1 mole of base</td>
<td>19</td>
<td>40.4</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>a) I don't know</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) That's by my calculation</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. If you used Sulphuric acid in the titration instead of hydrochloric acid, what would be the concentration of sulphuric acid?</td>
<td>Same as the first one calculated</td>
<td>a) As far as the volumes remain the same and concentration of the NaOH is still .1M</td>
<td>5</td>
<td>10.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) The mole ratio is 1:1</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) Since H₂SO₄ is a strong acid and highly dissociated</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Twice as much</td>
<td>a) Because there's 2:1 ratio of acid to base</td>
<td>6</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Because you need 2 moles of NaOH to 1 mole of H₂SO₄</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Half as much</td>
<td>a) Since you're getting 1 mole of OH⁻ from NaOH and 2 moles H⁺ from H₂SO₄</td>
<td>7</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) There's 1 mole of NaOH to each ½ mole of H₂SO₄</td>
<td>19</td>
<td>40.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) I don't know</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>I don't know</td>
<td>2</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Continued ...
<table>
<thead>
<tr>
<th>Questions</th>
<th>Students Predictions</th>
<th>Explanations</th>
<th>No. of Students</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. If instead of sodium hydroxide you had used Sodium Carbonate to titrate hydrochloric acid, what would be the concentration of the hydrochloric acid?</td>
<td>Same as the first one calculated</td>
<td>a) Since there's a 1:1 ratio between Na₂CO₃ and HCl</td>
<td>16</td>
<td>34.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Since the same volumes as obtained in the titration are used and the concentration of Na₂CO₃ remains at 0.1M</td>
<td>3</td>
<td>6.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c) Because if you use the same acid concentration won't change</td>
<td>1</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>d) Because HCl is a strong acid</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Twice as much</td>
<td>There are 2 moles of acid to 1 mole of Na₂CO₃ in balanced equation</td>
<td>18</td>
<td>38.3</td>
</tr>
<tr>
<td></td>
<td>Half as much</td>
<td>2 moles of HCl react with a mole of Na₂CO₃</td>
<td>4</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>a) I don't know</td>
<td>2</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) Since Na₂CO₃ is a weaker base there will be less OH⁻ ions</td>
<td>1</td>
<td>2.1</td>
</tr>
</tbody>
</table>
(2:1 mole ratios) posed in the study only 27.7% of the subjects predicted correctly in all three situations (Table 33). Seventeen percent made correct predictions in two situations while 31.9% predicted correctly in only one situation. A substantial number of subjects (23.4%) failed to make even one correct prediction. This finding is in agreement with the dominant conceptual error made by the subjects on the Volumetric Analysis Test (Table 22). It shows that in general, the students can successfully solve volumetric analysis problems involving 1:1 stoichiometric ratios but encounter difficulties with situations involving 2:1 stoichiometric ratios. This condition may relate to the possibility that these students have difficulties with the balancing of equations and the writing of formulas (see Table 34 and the later discussion on it). It could also be that problems given to the subjects normally involve a 1:1 mole ratios. This may be supported by the statements made by some of the subjects (when they were asked why they did not write equations for the HCl-NaOH reaction) that they were familiar with the reaction.

The finding that none of the subjects using the P(V) approach made a correct prediction in all three situations probably supports the contention that this approach is conceptually more difficult than the others. However, the finding that a substantial number of those using the F(B) and F(V) approaches obtained incorrect solutions seemed to indicate that their difficulty may lie in the use of the coefficients
in the balanced equation. The examination of the calculations and predictions of the students indicated that even though some of the students obtained the correct coefficients in the balanced reactions concerned, they became confused over whether to divide or multiply by the coefficients. This suggests some confusion in their minds over whether there is a direct or inverse relation between the stoichiometric moles and the actual moles used in the reaction. This is similar to the 'reversal of mole ratio' identified as one of the conceptual errors on the Volumetric Analysis Test (Table 22). It also suggest that part of the difficulties encountered in obtaining solutions to the three problems lie in their inability to co-ordinate the stoichiometric ratio with other relevant sources of information. In the case of those using the variant of the Proportional Approach, P(V), part of their difficulties lie in their inability to co-ordinate the mole ratio with the inverse proportional relation between the molarity and volume of the reacting solutions (Figure 15). For those using the Formula Approach, the difficulty involves their inability to co-ordinate the mole ratio with the moles of base (for those using the F(B) Approach) (see Figure 12) and with the formula: \( M_A V_A = M_B V_B \) (for those using the variant form, F(V)) (see Figure 13). It is possible that since these formulas are usually given without considering mole ratios other than 1:1 mole ratios, students either have difficulties in using different mole ratios in the formula or they apply the degenerate case, which is 1:1 (Table 34).
In the first question in Table 34 where the ratio between the acid and the base is 2:1, about 40% of the subjects gave an incorrect response by predicting that the acid concentration will be half as much as the one calculated for HCl in the initial task. However, they correctly indicated in their explanations that the mole ratio between the acid and the base was 2:1. Thus, although, they know the mole ratios, these students divide the moles of base by two to obtain the moles of acid. To reiterate what has been said before, there seems to be some confusion in their minds over whether to divide or multiply by the coefficients. They therefore don't seem to have a clear understanding of the relationships involved.

In question two, about 57% of the subjects correctly predicted that the molarity will be half. With the exception of one of these students who couldn't explain his prediction, all the others reasoned correctly. However, there are differences in the first two explanations offered for this prediction. While the second one derives from the mole relationship in the balanced equation, the first explanation derives from the number of OH\(^-\) and H\(^+\) in the reactants. This distinction is important because as will be seen below, this latter reason, based on the number of particles in the reactants, led some subjects to make incorrect predictions. In all, more than 40% of the subjects predicted incorrectly on this question. Those who predicted that the concentration will be twice as great explained either by saying that there's
a 2:1 ratio between the acid and base or 2:1 ratio between the base and acid. The students who gave the first reason derived the mole ratio from the molecular formulas without bothering to write balanced equations. As such, since they knew that H₂SO₄ has two hydrogen ions, they concluded that its concentration should be twice as great. Those who gave the second reason (4.3%) seem to know the stoichiometric ratio in the balanced equation. However, they were confused as to whether they should divide or multiply by the ratio.

About 21% of the subjects indicated that the concentration of the H₂SO₄ will be the same as that of the HCl calculated in the initial task. Three main reasons were offered. 10.6% of the subjects indicated that the molarity would be the same because "we're using the same volumes and concentration of base as we used in the first calculation, only the sulphuric acid is different". These students did not consider the mole relationship; they only paid attention to the volumes and the initial concentration of the base. The second reason given was that the mole ratio is 1:1. These students failed to write balanced chemical equations or even the formula for sulphuric acid. They just assumed a 1:1 ratio. The third reason given was that, just like hydrochloric acid, the sulphuric acid is a strong and highly dissociated acid, as such both should have the same concentration. Here, the students focus on only the strength of the acid and fail to take cognisance of the number of H⁺ ions in the two acids.

In the third question, just about 38% of the subjects
predicted and explained correctly that the concentration will be twice because of the 2:1 mole ratio between HCl and Na₂CO₃. However, the majority of the subjects made incorrect predictions. Those who predicted that the concentration will be half (8.5%) reasoned that in the balanced equation 2 moles of HCl react with 1 mole of Na₂CO₃. Although these subjects knew the mole ratio, they reversed the order of the mole ratio in their calculations. Those who indicated that the concentration will be the same (about 47% of the subjects) gave four main reasons. In the first reason which was given by 34% of the subjects, they indicated that HCl and Na₂CO₃ react in a 1:1 mole ratio. Some of these students had difficulties in writing a correct formula for Na₂CO₃ and in writing a correctly balanced equation for the reactants. Most students wrote the formula for sodium carbonate as NaCO₃. In the second reason which was given by 6.4% of the total sample, the students indicated that the concentration will be the same since the data obtained in the initial titration is being used. Again these subjects did not consider the mole relationship. They only considered the volumes and concentration obtained in the experiment. As already noted above, it is possible that since formulas are usually provided in texts without consideration of mole ratios other than 1:1, these students, therefore apply learned formulas without considering the coefficients of the reactants in a balanced equation. The third explanation was given by one subject. This subject indicated that since HCl is being used in the reaction, its
concentration should be the same as in the first calculation. In his calculations, this subject assumed a 1:1 mole ratio between Na₂CO₃ and HCl. The fourth explanation was that HCl is a strong acid and hence its concentration will remain the same as in the original calculation. These students failed to write a balanced equation in order to determine the mole relationship between the reactants. They only focused on the strength of the HCl.

Of the three subjects who gave the 'Other' response in question three, two indicated that they did not know how to do the calculation whilst one used an equilibrium constant equation for the dissociation of Na₂CO₃ to determine its concentration. This subject explained that since Na₂CO₃ is a weaker base the concentration of OH⁻ ions derived from its hydrolysis will be small compared to NaOH.

In general, it could be stated that, the subjects have various difficulties in computing the concentration of solutions used in titration when the mole ratio between the reactants is 2:1. However, with titrations involving substances reacting in a 1:1 ratio these difficulties don't exist. Some of the difficulties encountered by the subjects include:

a) inability to co-ordinate the stoichiometric ratio with other relevant data (confusion over whether to divide or multiply through by the reacting coefficients, focusing on only the volumes and molarities without taking into account the mole ratios, or focusing on only the strength of the reactants),
b) assumption of direct proportionality between molarity and volume, especially for those using the P(V) approach,
c) neglecting to write balanced equations and correct formulas,
d) deriving mole ratios from molecular formulas instead of from the balanced equations.

Finally, with reference to the research question stated at the beginning of this section, it could be concluded that the students basically use two approaches with their variations in solving volumetric analysis problems. These approaches are the Formula Approaches which involve the use of formulas and the Proportional Approaches which entail the utilization of proportional relationships existing among the variables in the problem.

Relationship Between Prior Number of Titrations and Performance on VAT

To understand whether involvement in titration experiments influences students' success on the Volumetric Analysis Test, the number of titrations done by each subject was obtained and correlated with their scores on the VAT.

The specific research question addressed was:

Research Question 7:
Is the number of laboratory titrations performed related to subjects' performance on the Volumetric Analysis Test?

Statistical Hypothesis:

There will be no statistically significant correlation between the subjects' scores on the written Volumetric
Analysis Test and the number of prior laboratory titrations completed since Grade 11. The analysis of the relation between performance on volumetric analysis problems and the number of laboratory titrations performed since Grade 11 for the entire study sample gave a Pearson product-moment correlation coefficient of 0.217. This value was significant beyond the .05 level. However, the low value of the correlation suggests that involvement in actual titrations may not strongly enhance performance on the volumetric analysis calculations. This low correlation between performance and the degree of involvement in laboratory titrations lends credence to Hearle's observation (cited in Doran, 1978) that students who learn manipulatory skills do not always perform well on cognitive based examinations.

It is suggested that this finding may reflect the objectives chemistry teachers have for laboratory work. If the aim for doing lab work is to keep the students busy (or to improve their manual skills) then it might not be surprising that there is very little relationship between them. On the other hand, if the aim is to reinforce theoretical understanding (as has been stated by chemistry teachers elsewhere (Thompson, 1975)), then one would expect a high relationship. However, since the aims the chemistry teachers have for lab work is not known, no specific implications can be drawn.

One other possible suggestion for the low correlation could be that normally some students are taught how to solve volumetric analysis problems long before they do the laboratory
experiments related to those problems. As such they may excel in the calculations without even knowing how the data used in the calculations were generated.

Relation of Student Difficulty Data to the Validated Model

In this last section the interview results and the conceptual errors made by the subjects on the volumetric analysis calculations (VAC) are related to the validated models.

The analysis of the steps in the subjects' solution to the volumetric analysis problems showed that most of the conceptual errors made by the subjects relate to specific prerequisite content. For example, a large number of subjects who wrote the Volumetric Analysis Test, made errors in writing molecular formulas or calculating molar masses for some chemical compounds. Quite a large percentage (70%) made an incorrect assumption of 1:1 ratio in problems requiring 2:1 mole ratios. These errors were also noted in the interview sample where most students had difficulties in writing correct formulas or correctly balanced equations. This finding relates to the significance of the direct effect of subsumed prerequisite concepts (SC) on performance on volumetric analysis calculations (VAC) in the validated model for the two groups of subjects who use algorithms with or without understanding. Those who obtained high scores on the volumetric analysis test employed mainly formulas in their solutions. That is, most students did not use the inverse relation between molarity and volume in their solutions to the volumetric analysis calcula-
tion problems. This is borne out by the small percentage of the interview subjects who employed the Proportional Approach in their solution to the volumetric analysis problems. But even with those who used the Proportional Approach many of them failed to see the kind of proportional relationship existing between molarity and volume. They assumed the relation to be a direct one. This gives considerable substance to the stronger direct effect of subsumed concepts on VAC when compared to the direct effect of inverse proportional reasoning on VAC. That is, the use of formulas (coupled with a possible understanding of its meaning) instead of proportion seem to have contributed to the small direct effect of inverse proportional reasoning on volumetric analysis calculations. Even those who could reason using inverse proportion seem to use formulas in their solution to the volumetric analysis problems instead of using proportion. However, it seems that this probably increases the indirect effect of inverse proportional reasoning on VAC via knowledge of subsumed prerequisite concepts.

This analysis applies to the validated model for the two groups of subjects identified in the study. However, the significant but low value for the path between knowledge of subsumed concepts and VAC for the subjects using algorithms with understanding could probably be explained by referring to the approaches used in solving the volumetric analysis-type problems in the interview. This group of students which includes most of the medium to high ability group, employed
mainly the Formula Approach in their solution, as found in the interview. However, in using the formulas for situations involving 2:1 mole ratios, some of these subjects become confused as to whether to divide or multiply by the mole ratio. That is, they have difficulty in coordinating the stoichiometric ratio with the formula they were using, thereby probably reducing the influence of subsumed concepts on VAC.

For subjects who use 1:1 mole ratios indiscriminately, the results of the model testing seemed to indicate that their ability to reason using inverse proportion may be suppressed to some extent by their ability to reason using direct proportion. This seems to be borne out by the interview data in that these subjects who make up a large proportion of the low ability group in the interview sample were found to establish a direct proportional relation between molarity and volume instead of an inverse relation. These subjects therefore, tend to use direct proportion in situations requiring inverse relation, which implies that their ability to reason using direct proportion suppresses or hides the true effect of inverse proportional reasoning in these situations. This is especially likely if subjects using the Proportional Approach to solve a problem fail to examine the logical (proportional) relationships involved in the problem.

In general, the arrangement of the variables in the validated models and the information obtained from other sources - conceptual errors and the interview results - suggest
that knowledge of subsumed prerequisite concepts and the ability to reason correctly using inverse proportion may influence performance on volumetric analysis calculations. This corroborates the finding in the previous chapter that both knowledge of subsumed concepts and inverse proportional reasoning influence performance on volumetric analysis calculations. For the subjects using algorithms with understanding, the validated model shows that both inverse proportional reasoning and subsumed concepts have direct influence on volumetric analysis calculations. For subjects using algorithms without understanding, inverse proportional reasoning affect volumetric analysis calculations mainly through its interaction with subsumed concepts while subsumed concepts affect volumetric analysis calculations directly.
CHAPTER VII

SUMMARY AND IMPLICATIONS

In this chapter, a brief review of the study, its objectives and major findings are presented. The limitations of the study, implications inferred from the interpretation of the findings, and suggestions for future research are also discussed.

Summary

Purpose

The first part of this study was designed to integrate two psychological theories (Gagné's cumulative learning theory and Piaget's theory) that are prominent in the field of science education research in order to investigate the influences among inverse proportional reasoning, direct proportional reasoning, knowledge of subsumed prerequisite concepts and performance on volumetric analysis calculations. The proposed integrated model was evaluated using recent approaches recommended for validating causal models. The model evaluation was done by using the observation data for the
two groups of subjects identified in the study on the basis of whether they used algorithms with or without understanding.

A second set of questions was designed to examine specific difficulties that students have with volumetric analysis. The conceptual errors made by the subjects while solving volumetric analysis problems were identified. In addition, the conceptual understanding and manipulatory skills that a subsample of the subjects brought to an actual titration situation were also investigated. In doing this, the approaches used by the subjects in solving volumetric analysis problems were identified.

The study was exploratory in its attempt to investigate the effect of the variables as postulated in the integrated model.

**Procedure**

Data collection instruments developed for this study included:

1. the Classroom-Proportionality Test with its two subtests,
   a) direct proportionality subtest and
   b) inverse proportionality subtest,
2. the Subconcepts Test,
3. the Volumetric Analysis Test, and
4. the Laboratory Skills in Titration checklist.

The direct and inverse proportionality subtests measured the ability to reason using direct and inverse proportion, respec-
tively. The subconcepts Test was used to measure knowledge of lower order (prerequisite) concepts subsumed by volumetric analysis calculations. The Volumetric Analysis Test measured performance on volumetric analysis calculations. The Laboratory Skills in Titration checklist was used to identify the manual skills used by subjects involved in the interview.

All the instruments were administered to subjects following the Grade 12 chemistry course in eight schools. The sample size was 328. The final sample used to validate the proposed integrated model consisted of those students who completed all four tests in eight schools. The total sample size was 265 subjects. Six subjects were selected from each school on the basis of their performance on the Volumetric Analysis Test and interviewed on a titration task after completion of the tests. The total interview sample size was 47.

Analysis

The four instruments measuring direct proportional reasoning, inverse proportional reasoning, subsumed prerequisite concepts, and volumetric analysis calculations were pretested in the pilot study. The reliability of these instruments was determined using the LERTAP (Nelson, 1974) computer program. Descriptive data (means, standard deviations) were also obtained using the subprogram CONDESCRIPTIVE in the Statistical Package for the Social Sciences (Nie, et. al. 1975).

All the statistical hypotheses in the study were tested at the 5 percent level of significance. Path analysis techniques were used to evaluate the influences among the
variables in the model. Recent developments employing chi-square goodness of fit test were used in the evaluation. Effect decomposition of the total associations between variables was done to identify the different effects of the variables in the integrated model.

The steps used by the subjects in solving the problems in the Volumetric Analysis Test were examined for any conceptual errors.

The manual skills of the subjects were identified from the checklist used during the interview. The percentage of subjects using any particular skill in the checklist was computed. This was done for all the interview subjects together as well as for subjects grouped according to the number of titration labs done since grade 11. Correlation analysis was used to test the relationship between the number of titration labs done and performance on volumetric analysis calculations for all the subjects involved in the study.

The interview data were analysed using qualitative techniques. The conceptions of the subjects on pH, concentration, indicator behaviour and scientific terminology were analyzed in terms of the response patterns for all the subjects as a group. The data collected from the subjects as they calculated the concentration of the acid from their titration data were used to identify the approaches used by the subjects in their attempt to solve the problem. The analysis was based on whether a formula was explicitly employed or whether proportion was used. The data on the subjects' predictions about the concentration of the acid in the three predictive
situations posed in the later part of the interview were analyzed in terms of both the kind of prediction made and the reasons offered. These analyses were conducted in order to obtain a much broader and deeper understanding of the difficulties encountered by the subjects in volumetric analysis.

Results

The major findings of this investigation were:

Model Evaluation for Subjects Using Algorithms with Understanding

The evaluation of the integrated model for subjects using algorithms with understanding revealed that both the proposed integrated model and a trimmed integrated model in which the influence of direct proportional reasoning on subsumed concepts was assumed to be zero, offered plausible representation of the causal influences in this group of subjects. However, the trimmed integrated model which offered a more parsimonious and meaningful explanation (in terms of the relative contributions of the direct and indirect effects) was selected. In this case too, the influence of direct proportional reasoning on knowledge of subsumed concepts was found to be mediated by inverse proportional reasoning. Also, direct proportional reasoning was found to have a strong positive effect on inverse proportional reasoning which also had a strong influence on subsumed concepts. However, both inverse proportional reasoning and subsumed concepts were found to have moderate but significant effects on performance of volumetric analysis calculations. The significant direct influence of inverse proportional reasoning on volumetric analysis calculations showed that, for
these students, their ability to use inverse proportional reasoning may significantly influence their performance on volumetric analysis calculations.

Model Evaluation for Subjects Using Algorithms Without Understanding

Even though both the proposed integrated model and a trimmed integrated model in which the influence of direct proportional reasoning and inverse proportional reasoning on subsumed concepts and volumetric analysis calculations, respectively, were found to account equally for the sample data, the trimmed integrated model was accepted as providing a more plausible interpretation of the performance of these subjects on the grounds of parsimony and the relative influence of the direct and indirect effects of the variables. For these subjects, the direct effects of direct proportional reasoning on inverse proportional reasoning and that of inverse proportional reasoning on subsumed concepts were found to be strong and positive. There was also a strong positive direct influence of subsumed concepts on volumetric analysis calculations. Here too, subsumed concepts were found to mediate the influence of inverse proportional reasoning on volumetric analysis calculations. Also, inverse proportional reasoning was found to mediate the influence of direct proportional reasoning on subsumed concepts. However, for these subjects, direct proportional reasoning appeared to suppress the influence of inverse proportional reasoning on volumetric analysis calculations, thereby making the direct path between the latter two
variables negative. This suppressive effect was found to be due to the fact that some of these subjects assumed a direct proportionality between molarity and volume in their solutions to the volumetric analysis problems.

Conceptual Errors

Eleven major conceptual errors were found in the steps used by the subjects to solve the volumetric analysis problems. This ranged from assuming an incorrect mole ratio for the reactants, assuming the concentration of a stock solution is different from the concentration of the volume used in the titration, to equating concentration to moles. Other errors included writing incorrect formulas or molar masses, assuming a direct proportional relation between concentration and volume, reversing stoichiometric mole ratios in their calculations, difficulties in using mass of substances to calculate molarity or vice versa and calculating the moles of a substance irrespective of its purity. Most of these errors were found to relate to the misunderstanding of the basic content in the area rather than to the logical structure of the problems.

Manual Skills

The analysis of the practical skills of the interview subjects showed that the adequacy of their skills varied with the specific skill in question. Thus, whereas most students exhibited satisfactory skills in setting up the
experiment, adding an indicator before titration, and shaking the titration flask, an equally large number of them failed to exercise caution when adding the basic solution to the acid or to use a white background to aid in detecting the colour changes of the indicator. This situation was attributable to the different emphases placed on the various manual skills by individual teachers.

A further analysis of the manual skills in terms of the degree of involvement in practical laboratory titrations showed that above a certain degree of involvement (above 5 practical labs) satisfactory manual skills are displayed by the subjects while below this number the skills are not as well developed.

Relation of Number of Titration Laboratories to Achievement

The correlation between the number of practical titration labs performed and performance on volumetric analysis calculations was found to be weak. That is, the number of practical labs performed by the students did not seem to strongly influence their performance on volumetric analysis calculations.

Concentration and its Relationship to Mole

The interview subjects were found to show adequate understanding of the concepts of concentration and mole. Most of them understood that the concentration will vary with dilution, but will remain invariant when the volume of the
solution is decreased. Similarly, almost all of them indicated that the number of moles of a substance in a solution will remain invariant with dilution. However, almost half the subjects indicated that the number of moles will also remain invariant when some of the solution is removed.

\[ \text{PH} \]

The analyses of the students' conceptions about pH indicated that they did not have any difficulties with certain aspects of pH. They could calculate the pH of strong acidic and basic solutions from their concentrations; they knew the pH at the stoichiometric point for the reaction between HCl and NaOH was 7; and they also realized that the pH increased with the addition of a basic solution.

However, difficulties were encountered in other areas:

1. Most students (81%) could not correctly indicate the effect of dilution on the pH of acid solutions,
2. About half of the students could not correctly indicate the differences in the rate of change of pH at the initial stages of titration and near the end, and
3. About half of the subjects held the view that the pH at the stoichiometric point for the titration of a strong acid with a weak base or a strong base with a weak acid will be 7.
Indicator Behaviour

Most of the students were found to show an understanding of the function of indicators in acid-base titrations. However, in selecting indicators for titrations, most students did not relate the pH range of the indicator to the stoichiometric point for the reaction under study. Most of the explanations offered related to their own laboratory experiences. In the case of the titration of a strong acid with a strong base, the students did not realize that the wide range of pH change at the stoichiometric point allows for the use of a wide variety of indicators.

Most of the students were also found to view indicators as neutral substances whose relative volume does not affect the titration results.

In trying to explain the colour changes which occur in titration only 31.9% of the students referred to the equilibrium between the dissociated and undissociated forms of the indicator.

Terminology

The students showed an inadequate understanding of the terms: endpoint and stoichiometric point even though they used them frequently.

Approaches to Problem Solution

Two principal approaches were used by the subjects in calculating the molarity of the acid from the data obtained
in the titration. These were the Formula Approach and the Proportional Approach. Two forms of these approaches were identified, namely, the basic and the variant forms. 46.8% of the subjects used the basic form of the Formula Approach while 25.5% used the variant form. Also 12.8% of the subjects used the basic form of the Proportional Approach while 8.5% used the variant form of the Proportional Approach. Thus, over all a large number of the subjects used the Formula Approach in their solutions. It was also found that subjects in the low achievement group used the Proportional Approach to a greater extent than those in the middle and high achievement group. Those using the variant of the Proportional Approach were found to assume direct proportionality between molarity and volume of solution. The analysis of the approaches also indicated that a large proportion of the subjects did not write balanced equations in their solutions while a substantial number did not indicate the mole ratios in the reaction.

Furthermore, the initial problem involving the titration of NaOH against HCl was successfully solved by 78.7% of the subjects while only 27.7% of the subjects predicted correctly in all the three situations involving 2:1 mole ratios. About 23% failed to make at least one correct prediction. This difficulty was attributed to the fact that some of the subjects assumed 1:1 mole ratios in their predictions while others were unable to coordinate the stoichiometric ratio with other relevant data.
Delimitations of the Study

The topic chosen for the study, namely, volumetric analysis, is a broad one involving several concepts, laboratory skills, volumetric analysis calculations and the mechanical process of titration. Other subsidiary components are the role of indicators in titration, use of oxidation-reduction reactants, the pH of acidic and basic solutions, the construction and interpretation of titration curves, and back titrations.

The restriction of this study to some selected aspects of volumetric analysis (titration calculations, laboratory skills, role of indicators and pH) without considering oxidation-reduction reactions as well as titration curves per se is recognized as a delimitation of the study. The restriction of the prerequisite concepts to a selected set of subsumed prerequisite concepts also represents an important delimitation of the study. However, other researchers (Gower, Daniels and Lloyd, 1977a; Toon and Ellis, 1973) have proposed similar prerequisite concepts for volumetric analysis calculations. In any case, note is taken of the possibility that different researchers may hypothesize other subsumed concepts in addition to the ones used in the study. Also cognisance is taken of the possibility that other researchers may wish to stress other aspects of volumetric analysis instead of the ones chosen for this study.

A further delimitation is the use of students in only one grade level (Grade 12) in one Canadian City (Vancouver). It is noted that even in the same school,
students with different motivations or interests may respond differently (Lovell, 1971b) to the tests. Volunteer subjects were used and the optional nature of the course puts the subjects in a self-selective group. Thus, while any results from the study may be suggestive, one has to be cautious in generalizing to other situations. However, one consolation is that in British Columbia Schools the unit on acids and bases which includes volumetric analysis is taught only in the Grade 12 chemistry course even though in Grade 11 students perform one practical experiment on titrations.

**Implications**

Although the study is exploratory, a number of implications can be inferred from the interpretation of the results. The finding that the performance of subjects using 1:1 mole ratios indiscriminately and those using 1:1 mole ratios discriminately are explained by two different trimmed integrated models seems to suggest that these groups of students may have different cognitive strategies and also that they may differ in other important ways. It also points to the appropriateness of grouping chemistry students on the basis of their comprehension of the mole ratios in a balanced chemical reaction. If chemistry teachers are aware of this difference they may be in a better position to help improve the strategies used by those students who apply the 1:1 mole ratios indiscriminately in their calculations. The finding that for both groups of subjects, subsumed concepts and
proportional reasoning had important effects, points to the probable usefulness in combining the Gagnéan and Piagetian theories into a single model which could be used to explain a subject's difficulties with chemical problems. For the subjects using algorithms without understanding, the finding that the direct effects of inverse proportional reasoning on volumetric analysis calculations is negligible supports the notion expressed by others (e.g. Wheeler and Kass, 1977) that the content of a task may be more important than the structure. However, the considerable indirect influence of inverse proportional reasoning on volumetric analysis calculations through subsumed concepts implies that inverse proportional reasoning may interact with subsumed concepts. It also suggests that the theoretical assertion that inverse proportional reasoning may have a direct influence on performance on chemical problems may not be completely justified. For the subjects using stoichiometric ratios with understanding, the significance of the direct influence of inverse proportional reasoning on volumetric analysis calculations indicates that these subjects probably identify and apply the correct relationship between molarity and volume of solution.

The negligible direct effect of direct proportional reasoning on knowledge of subsumed concepts for both groups suggests that since inverse proportional reasoning is a later development (e.g. Rogers, 1977), the effect of direct proportional reasoning on subsumed concepts may be channelled through inverse proportional reasoning as soon as this later ability is developed.
Although other researchers (Lovell and Butterworth, 1966) have suggested that both inverse and direct proportional reasoning may be measuring the same intellective ability, the present data (Cronbach's alpha for CPT = .50) show that for the study sample, the two variables may be measuring different abilities.

The interview results and the results of the conceptual errors point to the need for teachers to be aware of the assumptions which students may have in a given teaching situation so as to adopt teaching strategies which will minimize such misconceptions. The poor understanding of the concepts (pH, indicator behaviour and concentration) as they are manifested in titrations suggests a move away from the highly prescriptive "cook-book" laboratory which occurs in most schools to a less prescriptive type. The adoption of the less prescriptive type may help students to understand the possible implications and explanations of their actions and observations during practical work. This type of practical work may require the students to make decisions on their own in the selection of equipment and solutions for practical work. It is to be hoped that these decisions would tend to be based on a sound chemical knowledge rather than on the students' familiarity with the equipment or solutions. The chemistry teacher can facilitate this process through asking questions (such as those used in the interview) which can identify the students' reasoning at various stages in the investigation. As some of the students reported that they have "never been asked these kinds of questions", it seems that an emphasis on the students' understanding of the
processes occurring during an investigation may go a long way toward improving their general understanding of chemical concepts. It will also help the students to integrate in a meaningful way, the various concepts which they have learned in isolation in different lessons.

In order to provide ample time for chemistry teachers to effect this less prescriptive approach, it seems that chemistry instruction in the secondary school may have to move away from the encyclopedic coverage of the concepts to teaching fewer concepts for greater conceptual understanding.

The onus may also be placed on curriculum writers. They also have to move away from the usual practice of providing "cook-book" type experiments in laboratory texts written for students.

Also, the poor understanding shown on the concepts entailed in a titration and the inadequate manual skills displayed by the subjects points to the need for teachers to examine the objectives that they may have for practical work and whether these are communicated well to the students.

The finding that the students use mainly two approaches (proportional and formula approaches) to solve volumetric analysis problems may have important educational implications. It may tell teachers that as well as a particular approach fostered by them, the students may employ other approaches. With this knowledge, instead of stressing only one particular approach in their teaching, the teachers can emphasize possible alternate routes to the solution of the problems so that students whose learning styles or processing abilities make them
comfortable with the alternative routes may also gain insight into the problem.

Also, the finding that a high percentage of those using the Formula Approach obtained correct answers to the problems, may suggest that teachers may have to encourage more students to use this approach. However, they have to be aware that blind emphasis on the use of formulas without considering whether the students understand the relationships among the variables entailed by the formulas may lead the student nowhere and hence must be guarded against.

**Future Research**

The results and implications of the study suggest the following areas for future research:

1. In order to identify the stability of the trimmed integrated models as a plausible explanatory systems for subjects' performance on chemical concepts, the need exists for a replication of this study in other geographical areas and with other chemical concepts. In such a study, it may be necessary to gather further qualitative data on the relationship between direct proportional reasoning and the subjects' understanding of the subsumed prerequisite concepts so as to allow a full interpretation of the model. This model testing could be done for chemistry subjects grouped according to their use of the stoichiometric ratio in calculations.

2. The use of qualitative data to explain some of the quantitative results points to the need for further investigation
of the role of qualitative information as a supplement to quantitative data.

3. Since the students were found to exhibit different levels of skills in their titration and also showed some misunderstanding of some of the concepts entailed by a titration, it seems necessary to examine the objectives that teachers have for practical work. Such a study could be conducted by using a questionnaire as was done in the United Kingdom by Kerr (1963) and Thompson (1975). The questionnaire could be used in conjunction with the observation of actual practical work in the schools. Hopefully, this would reveal any differences in the emphases given to different objectives. It would also reveal whether developing an understanding of the processes occurring during laboratory investigation is considered important. Also, the results of such a study would provide curriculum developers and revisors with a base for action.

Also, the misunderstandings displayed by the interview subjects on pH, indicator behaviour etc., during the titration, points to the need for further studies aimed at examining the kinds of understanding that groups of students have when performing laboratory experiments. In doing this, it may be necessary to consider other variables such as the students' interest in chemistry and their future aspirations. These additional variables may tell us why certain subjects perform the way they do.
REFERENCES


137. Wilkins, M.C. The effect of changed material on ability to do formal syllogistic reasoning. Archives of Psychology, 1928, (102), 1-83.


APPENDIX A

VOLUMETRIC ANALYSIS TEST
VOLUMETRIC ANALYSIS TEST

Name: __________________________
School: _________________________
Date of Birth: ____________________
   month   day   year
Date: ____________________________
No of Titrations: ________________

This is a test of how you arrive at solutions to certain chemical problems. It is therefore very important that you show all your work in the spaces provided.

Please use the following atomic masses:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>12.0</td>
</tr>
<tr>
<td>Chlorine</td>
<td>35.5</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>1.0</td>
</tr>
<tr>
<td>Oxygen</td>
<td>16.0</td>
</tr>
<tr>
<td>Sodium</td>
<td>23.0</td>
</tr>
<tr>
<td>Sulphur</td>
<td>32.0</td>
</tr>
<tr>
<td>Calcium</td>
<td>40.0</td>
</tr>
<tr>
<td>Barium</td>
<td>137.0</td>
</tr>
</tbody>
</table>

DO ALL QUESTIONS.
1. What volume of $0.02 \text{ M} \text{H}_2\text{SO}_4$ is required to react completely with 20.0 mL of 0.04 M NaOH?

2. 0.50 M NaOH is used to determine the molar concentration of a $\text{H}_2\text{SO}_4$ solution. What is the molarity of the acid, 20.0 mL of which is just neutralized by 36.0 mL of NaOH?
3. 0.500 g of an impure sample of barium hydroxide was added to 50.0 mL of 0.100 M HCl. The excess HCl was then titrated with 7.50 mL of 0.200 M NaOH. What is the mass of pure barium hydroxide in the sample?

4. If 25.0 mL of 0.5 M HCl neutralizes 30.0 mL of a 250.0 mL stock solution of NaOH, what is the molarity of the 250.0 mL stock solution?
5. How many milliliters of 0.20 M NaOH are required to neutralize 50.0 ml of 0.10 M HCl?

6. If 30.0 ml of HCl is required to react completely with 0.50 gram sample of Na₂CO₃, what is the molarity of the acid?
7. If 25.0 mL of 0.5 M Na₂CO₃ solution neutralizes 25.0 mL of HCl. What is the concentration of HCl?

8. How many milliliters of 0.10 M HCl are required to react completely with 0.40 g of Na₂CO₃?
9. What volume of 2 M Na₂CO₃ solution will neutralize 200.0 mL of 1.0 M H₂SO₄ solution?

10. 100.0 mL of a solution of NaOH is neutralized by 20.0 mL of 2.0 M H₂SO₄. What is the mass in grams of NaOH in the solution used?
11. NaOH solution can be used to neutralize sulphuric acid

\[
\text{NaOH} + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + \text{H}_2\text{O} \quad \text{(Unbalanced)}
\]

What volume of 1 M NaOH solution will neutralize 1.0 litre of 1 M \( \text{H}_2\text{SO}_4 \)?

12. If 25.0 mL of \( \text{Na}_2\text{CO}_3 \) solution is neutralized by 50.0 mL of a 0.50 M HCl, what is the weight in grams of the sodium carbonate in the solution.
13. 1/2 litre of 1 M \( \text{Ca(OH)}_2 \) is completely neutralized by 1 litre of a solution of HCl. What is the molarity of the HCl?

14. A 500 mL solution of HCl is prepared for use in a class experiment. If 40.0 mL of this neutralizes 25.0 mL of 1.0 M \( \text{Na}_2\text{CO}_3 \) solution, what is the concentration of the original solution of HCl?
15. A 2.0 gram sample of benzoic acid, \( C_7H_5O_2H \) (molar mass = 122.0) requires 50.0 mL of NaOH solution to reach the end point. What is the molarity of the base?
APPENDIX B

CLASSROOM PROPORTIONALITY TEST

B.1. Answer Booklet

B.2. Testing Procedures For Each Item
NAME: ____________________________

Birthdate: ____________________________
  month  day  year

Sex: ____________________________

School: ____________________________

Date: ____________________________

Directions:

For each of the items below a situation will be demonstrated. Each demonstration will lead to a question for which there are a number of possible answers. For each item you are to check the box of the best answer and explain your choice in the space provided.

Example Item: "The Balancing Beam"

☐ Mark 3
☐ Mark 7
☐ Mark 8
☐ Mark 10
☐ Mark 11

Please explain your choice.
**Item 1:** "Plastic Cylinders 1"

The water will rise to mark:

- 7
- 8
- 9
- 10
- There is no way of predicting

Please explain your choice.

**Item 2:** "Plastic Cylinders 2"

The water will rise to mark:

- 5 1/3
- 5 2/3
- 7 1/3
- 8 1/3
- 9

Please explain your choice.
Item 3  "Plastic Cylinders 3"

The water will rise to mark:

- 11
- 15
- 5 1/5
- 1 2/3
- There is no way of predicting

Please explain your choice.

Item 4  "Plastic Cylinders 4"

The water will rise to mark:

- 2 4/3
- 4 1/3
- 7
- 39
- There is no way of predicting.

Please explain your choice.
Item 5  "Plastic Cylinders 5"

The water will rise to mark:

☐ 4
☐ 9
☐ 13
☐ 16
☐ There is no way of predicting

Please explain your choice.

Item 6  "Plastic Cylinders 6"

The water will rise to mark:

☐ 2
☐ 3 1/2
☐ 12
☐ 14
☐ There is no way of predicting

Please explain your choice.
**Item 7**  "Plastic Cylinders 7"

The water will rise to mark:

- 0
- 2
- 2 2/5
- 4
- 15

Please explain your choice.

**Item 8**  "The Balancing Beam 1"

Where would you hang the 5-unit weight to make the beam balance?

- between 3 and 4
- mark 7
- mark 12
- mark 14
- at the end

Please explain your choice.
Item 9  "The Balancing Beam 2"

Where would you hang the 4-unit weight to make the beam balance?

☐ mark 5
☐ mark 6
☐ between mark 6 and 7
☐ mark 7
☐ mark 10

Please explain your choice.

Item 10  "The Balancing Beam 3"

Where would you hang the 6-unit weight to make the beam balance?

☐ mark 1
☐ mark 3
☐ mark 4
☐ mark 7
☐ mark 9

Please explain your choice.
Item 11  "The Balancing Beam 4"

Where would you hang the 6-unit weight to make the beam balance?

- mark 3
- between mark 4 and mark 5
- mark 8
- mark 9
- mark 18

Please explain your choice.

Item 12  "The Balancing Beam 5"

Where would you hang the 6-unit weight to make the beam balance?

- mark 0
- between mark 2 and mark 3
- between mark 3 and mark 4
- mark 9
- mark 10

Please explain your choice.
Item 13  "The Balancing Beam 6"

Where would you hang the 12-unit weight to make the beam balance?

- between mark 1 and mark 2
- between mark 2 and mark 3
- mark 6
- mark 19
- mark 40

Please explain your choice.

Item 14  "The Balancing Beam"

Where would you hang the 2-unit weight to make the beam balance?

- between 0 and mark 1
- between mark 1 and mark 2
- mark 4
- mark 16
- mark 40.
testing procedures for each item

classroom proportionality test

example: "the balance beam"

materials:
1 balance beam
2 10-unit hanging weights

directions:
show the students the balance beam and the two 10-unit hanging weights. point out the equally spaced marks along the length of the beam and how the beam balances like a teeter totter when no weights are hung on it. hang a 10-unit weight on one side of the beam at the 7th mark.

ask: where should the other 10-unit weight be hung to make the beam balance?
Item 1: "Plastic Cylinders 1"

Materials: 1 wide plastic cylinder (3.8 cm in diameter)
1 narrow plastic cylinder (2.5 cm in diameter)
1 jar of coloured water

Directions: Show the students the two plastic cylinders. Point out the different diameters and the equally spaced marks along the front of each. Pour water from the jar into the wide cylinder up to the 4th mark. Pour that water into the narrow cylinder and note that the water rises to the 6th mark. Tell the students to make a record of this information. Pour the water from the narrow cylinder into the jar. Pour water from the jar into the wide cylinder up to the 6th mark.

Ask: How high would this water rise if it were poured into the narrow cylinder?

Item 2: "Plastic Cylinders 2"

Materials: Same as for Item 1

Directions: Start with empty cylinders. Pour water from the jar up to the 11th mark in the narrow cylinder.

Ask: How high would this water rise if it were poured into the wide cylinder?

Item 3: "Plastic Cylinders 3"

Materials: 1 wide plastic cylinder (3.8 cm in diameter)
1 narrow plastic cylinder (1.8 cm in diameter)
1 jar of coloured water

Directions: Show the students the two plastic cylinders. Point out the different diameters and the equally spaced marks along the front of each. Point out that the wide cylinder is the one used in the previous demonstrations. Pour water from the jar into the wide cylinder up to the 3rd mark. Pour that water into the narrower cylinder and note that the water rises to the 9th mark. Tell the students to make a record of this information. Pour the water from the narrower cylinder into the jar. Pour water from the jar into the wide cylinder up to the 5th mark.

Ask: How high would this water rise if it were poured into the narrower cylinder?
**Item 4:** "Plastic Cylinders 4"

**Materials:** Same as for Item 3

**Directions:** Start with empty cylinders. Pour water from the jar up to the last mark (13th mark) in the narrower cylinder.

**Ask:** How high would this water rise if it were poured into the wide cylinder?

**Item 5:** "Plastic Cylinder 5"

**Materials:** 1 plastic cylinder (2.5 cm in diameter)
1 narrow plastic cylinder (1.8 cm in diameter)
1 jar of coloured water

**Directions:** Show the students the two cylinders and point out the different diameters and the equally spaced mark on each. Pour water from the jar up to the 5th mark in the wider cylinder. Pour that water into the narrower cylinder and note that the water rises to the 10th mark. Tell the students to make a record of this information. Pour the water from the narrower cylinder into the jar. Pour water from the jar into the wider cylinder up to the 8th mark.

**Ask:** How high would this water rise if it were poured into the narrower cylinder?

**Item 6:** "Plastic Cylinder 6"

**Materials:** Same as for Item 5

**Directions:** Start with empty cylinders. Pour water from the jar up to the 7th mark in the narrower cylinder.

**Ask:** How high would this water rise if it were poured into the wider cylinder?

**Item 7:** "Plastic Cylinder 7"

**Materials:** 1 wide plastic cylinder (4.8 cm in diameter)
1 narrow plastic cylinder (3.8 cm in diameter)
1 jar of coloured water.

**Directions:** Show the plastic cylinder to the students. Point out the different diameters and the equally spaced marks. Pour water from the jar into the wider cylinder up to the 4th mark. Pour that water into the narrower tube and note that the water rises to the 10th mark. Tell the students to make a record of this information. Pour water from the jar into the narrow cylinder up to the 6th mark.
Ask: How high would this water rise if it were poured into the wider tube?

Item 8: "The Balancing Beam 1"

Materials: 1 balance beam
- a 10-unit hanging weight
- a 5-unit hanging weight

Directions: Show the students the balance beam and the two hanging weights. Hang the 10-unit weight 7 marks out from the fulcrum on one side of the beam. Point out that the 10-unit weight is hanging at 7 marks from the centre.

Ask: Where would you hang the 5-unit weight to make the beam balance?

Item 9: "The Balancing Beam 2"

Materials: 1 balance beam
- a 15-unit hanging weight
- a 10-unit hanging weight

Directions: Show the students the balance beam and the two hanging weights. Hang the 15-unit weight 4 marks out from the fulcrum on one side of the beam. Point out that the 15-unit weight is hanging at 4 marks from the centre.

Ask: Where would you hang the 10-unit weight to make the beam balance?

Item 10: "The Balancing Beam 3"

Materials: 1 balance beam
- a 2-unit hanging weight
- a 6-unit hanging weight

Directions: Show the students the balance beam and the two hanging weights. Hang the 2-unit weight 3 marks out from the fulcrum on one side of the beam. Point out that the 2-unit weight is hanging at 3 marks from the centre.

Ask: Where would you hang the 6-unit weight to make the beam balance?

Item 11: "The Balancing Beam 4"

Materials: 1 balance beam
- a 9-unit hanging weight
- a 12-unit hanging weight

Directions: Show the students the balance beam and the two hanging weights. Hang the 12-unit weight 6 marks out from the fulcrum on one side of the beam. Point out that the 12-unit weight is hanging at 6 marks from the centre.

Ask: Where would you hang the 9-unit weight to make the beam balance?
Item 12  "The Balancing Beam 5"
Materials:  1 balance beam
           1 9-unit weight
           1 15-unit hanging weight
Directions: Show the students the balance beam and the two hanging
weights. Hang the 15-unit weight 6 marks out from the
fulcrum on one side of the beam. Point out that the
15-unit weight is hanging at 6 marks from the centre.
Ask: Where would you hang the 9-unit weight to make the
beam balance?

Item 13  "The Balancing Beam 6"
Materials:  1 balance beam
           a 12-unit hanging weight
           a 3-unit hanging weight
Directions: Show the students the balance beam and the hanging weights.
Hang the 3-unit weight 10 marks out from the fulcrum on one
side of the beam. Point out that the 3-unit weight is
hanging at 10-marks from the centre.
Ask: Where would you hang the 12-unit weight to make the
beam balance?

Item 14  "The Balancing Beam 7"
Materials:  1 balance beam
           a 20-unit hanging weight
           a 4-unit hanging weight
Directions: Show the students the balance beam and the hanging
weights. Hang the 20-unit weight 8 marks out from
the fulcrum on one side of the beam. Point out that
the 20-unit weight is hanging at 8 marks from the centre.
Ask: Where would you hang the 4-unit weight to make the
beam balance?
APPENDIX C

SUBCONCEPTS TEST
SUBCONCEPTS TEST

Name: __________________________

School: _________________________

Date of Birth: ____________________

Date: ____________________________

month day year

This is a multiple choice test of certain chemical concepts. Attempt all questions. Answer the questions by circling the appropriate letter.

Please use the following atomic masses:

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<thead>
<tr>
<th>Element</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Calcium</td>
<td>40</td>
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<tr>
<td>Carbon</td>
<td>12</td>
</tr>
<tr>
<td>Cesium</td>
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</tr>
<tr>
<td>Chlorine</td>
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<td>Copper</td>
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<td>Hydrogen</td>
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<tr>
<td>Iron</td>
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<tr>
<td>Magnesium</td>
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<tr>
<td>Oxygen</td>
<td>16</td>
</tr>
<tr>
<td>Sodium</td>
<td>23</td>
</tr>
<tr>
<td>Sulphur</td>
<td>32</td>
</tr>
</tbody>
</table>

DO NOT SPEND TOO LONG ON ANY ONE QUESTION WHICH YOU HAVE DIFFICULTY ANSWERING.
1. If 20.0 g of NaOH are dissolved in 200 mL of solution, what is the concentration of the solution?
   A. 0.5 moles per litre
   B. 1.5 moles per litre
   C. 2.0 moles per litre
   D. 2.5 moles per litre
   E. 3.0 moles per litre.

2. How many moles of NaOH are dissolved in 500 mL of 4 M NaOH solution?
   A. 1/2 mole
   B. 1 mole
   C. 1 1/2 moles
   D. 2 moles
   E. 3 moles.

3. What mass of NaOH is contained in 500 mL of 1M NaOH solution?
   A. 10 g
   B. 20 g
   C. 40 g
   D. 60 g
   E. 80 g

4. Which of the following HCl solutions is most concentrated?
   A. 500 mL of 2 M HCl
   B. 1000 mL of 3 M HCl
   C. 300 mL of 4 M HCl
   D. 800 mL of 5 M HCl.
   E. 500 mL of 6 M HCl
5. What is the volume of 6 M HCl solution that is required to prepare 300 mL of 1 M HCl?
   A. 50 mL
   B. 83 mL
   C. 600 mL
   D. 800 mL
   E. 1800 mL

6. 20 mL of 18 M H_2SO_4 is diluted to a total volume of 1.0 litre. What is the molar concentration of this solution?
   A. 0.36 M
   B. 0.72 M
   C. 9 M
   D. 12 M
   E. 360 M

7. What volume of 5 M NaOH is needed to prepare 200 mL of 2 M NaOH solution?
   A. 15 mL
   B. 20 mL
   C. 40 mL
   D. 80 mL
   E. None of the above

8. What volume of water must be added to dilute a solution of 2 M CaCl_2 to 1200 mL of 0.8 M CaCl_2?
   A. 92 mL
   B. 480 mL
   C. 720 mL
   D. 800 mL
   E. 1000 mL
9. Given this equation: \(2\text{SO}_2 + \text{O}_2 \rightarrow 2\text{SO}_3\)

What mass of \(\text{SO}_2\) would react with 32 g of \(\text{O}_2\)?

A. 32 g  
B. 64 g  
C. 96 g  
D. 128 g  
E. 130 g  

10. \(2 \text{NaOH} + \text{H}_2\text{SO}_4 \rightarrow 2\text{HOH} + \text{Na}_2\text{SO}_4\)

If 8.0 g of \(\text{NaOH}\) react with 9.81 g of \(\text{H}_2\text{SO}_4\) to produce 3.60 g of \(\text{HOH}\), then the mass of \(\text{Na}_2\text{SO}_4\) produced is:

A. 6.21  
B. 8.31  
C. 14.21  
D. 17.81  
E. 21.41  

11. In the reaction:

\(2\text{A} + 3\text{B} \rightarrow 2\text{C} + 4\text{D}\)

42.0 g of \(\text{A}\) reacts with 2.0 g of \(\text{B}\) to produce 20.0 g of \(\text{C}\).

If the molar mass of \(\text{C}\) is 10.0 g per mole, the molar mass of \(\text{D}\) in grams per mole is:

A. 4.0  
B. 6.0  
C. 12.0  
D. 24.0  
E. 40.0.
12. In the reaction:
\[ \text{C} + \text{O}_2 \rightarrow \text{CO}_2 \]

What mass of \( \text{O}_2 \) is required to react with 0.25 mole of carbon?
A. 4.0 g  
B. 8.0 g  
C. 16.0 g  
D. 64.0 g  
E. 128 g.

13. Assume sulphur was \( S_4 \) instead of \( S_8 \). 3.00 moles of sulphur would have a mass of:
A. 24.0 g  
B. 96.0 g  
C. 128.0 g  
D. 256.0 g  
E. 384 g.

14. The number of moles of NaCl in a two pound (908 g) box of table salt is:
A. 0.0644 mol  
B. 15.5 mol  
C. 58.5 mol  
D. 72.0 mol  
E. \( 5.31 \times 10^4 \) mol.

15. The mass of \( 6.02 \times 10^{23} \) molecules of carbon tetrachloride is:
A. 1.0 g  
B. 30 g  
C. 47.5 g  
D. \( 6.02 \times 10^{23} \) g  
E. 154 g.
16. The number of moles of atoms in 1.40 g of copper is:
   A. 0.0013
   B. 0.0220
   C. 0.250
   D. 0.50
   E. 88.9.

17. The number of moles of NaOH that would be equal in mass to 2.0 moles of CaCO₃ is:
   A. 2.00
   B. 2.50
   C. 3.33
   D. 5.00
   E. none of the above.

18. How many moles of sodium contains the same number of atoms as 0.5 moles of calcium?
   A. 0.5 moles
   B. 1.0 moles
   C. 23 moles
   D. 40 moles
   E. none of the above.

19. Calculate the mass of ammonia (NH₃) containing twice as many molecules as 32 grams of oxygen (O₂)
   A. 17 g
   B. 32 g
   C. 34 g
   D. 6.02 x 10²³ g
   E. None of the above.
20. How many moles of magnesium would weigh the same as six moles of carbon?
   A. 1.5 moles
   B. 3.0 moles
   C. 6.0 moles
   D. 12 moles
   E. None of the above.

21. In the reaction
   \[ \text{Cl}_2 + \text{C}_{10}\text{H}_{16} = \text{C} + \text{HCl} \] (unbalanced)
   the ratio of molecules of chlorine (Cl\(_2\)) reacting with molecules of C\(_{10}\)H\(_{16}\) is:
   A. 1:8
   B. 8:1
   C. 8:10
   D. 16:1
   E. None of the above.

22. Sulphuric acid + Aluminium hydroxide → Water + Aluminium sulphate
   The balanced equation for the above equation is:
   A. \( \text{H}_2\text{SO}_4 + \text{Al(OH)}_2 \rightarrow 2\text{HOH} + \text{AlSO}_4 \)
   B. \( \text{HSO}_4 + \text{AlOH} \rightarrow \text{HOH} + \text{AlSO}_4 \)
   C. \( 3\text{H}_2\text{SO}_4 + 2\text{AlH}_3 \rightarrow 6\text{H}_2 + \text{Al}_2(\text{SO}_4)_3 \)
   D. \( 3\text{H}_2\text{SO}_4 + 2\text{Al(OH)}_3 \rightarrow 6\text{HOH} + \text{Al}_2(\text{SO}_4)_3 \)
   E. None of the above.
23. \[ \text{NaOH} + \text{A1(NO}_3\text{)}_3 \rightarrow \text{A1(OH)}_3 + \text{NaNO}_3 \]

Balance the above equation using simplest whole numbers. The coefficient (number in front of) for A1(NO_3)_3 would be:

A. 1
B. 2
C. 3
D. 4
E. 5

24. Which of the following is NOT involved in balancing chemical equations?

A. Conservation of atoms
B. Conservation of mass
C. Conservation of energy
D. Conservation of molecules.
E. Conservation of electrons.

25. \[ 4\text{FeS}_2 + 11\text{O}_2 \rightarrow 2\text{Fe}_2\text{O}_3 + 8\text{SO}_2 \]

Which of the statements about the above equation is FALSE?

A. Four formula units of FeS_2 will produce eight molecules of SO_2.
B. Oxygen has 11 atoms per molecule.
C. These are four ions of Fe on the right hand side of the equation.
D. The name for Fe_2O_3 is ferric oxide.
E. SO_2 is gaseous.

26. Given: \[ \text{C}_3\text{H}_8 + \text{SO}_2 \rightarrow 3\text{CO}_2 + 4\text{H}_2\text{O} \]

Which of the following statements about the above equation is TRUE?

A. 2 molecules of C_3H_8 will react with 10 molecules of oxygen.
299

B. 1 molecule of $C_3H_8$ will produce 2 molecules of products
C. 1 molecule of $C_3H_8$ will react with 10 molecules of oxygen
D. The equation is not balanced
E. 5 atoms of $O_2$ produce 3 molecules of $CO_2$.

27. Consider the following equation:

$$2 \text{Al} + \text{Fe}_2\text{O}_3 \rightarrow 2 \text{Fe} + \text{Al}_2\text{O}_3$$

The TRUE statement about the equation is:
A. 2g Al will react with 1g of $\text{Fe}_2\text{O}_3$
B. 2 mole Al will produce 2 moles of Fe
C. 1g of $\text{Fe}_2\text{O}_3$ will produce 2 moles of Fe
D. 1 mole of $\text{Fe}_2\text{O}_3$ will produce 1g $\text{Al}_2\text{O}_3$
E. 2g Al produce 2g of Fe.

28. Given the reaction:

$$\text{H}_2 + \text{Cl}_2 \rightarrow 2\text{HCl}$$

The TRUE statement about the reaction is:
A. One atom of $\text{H}_2$ reacts with one atom of $\text{Cl}_2$ to form two molecules of HCl
B. $6.02 \times 10^{23}$ molecules of $\text{H}_2$ reacts with $6.02 \times 10^{23}$ molecules of $\text{Cl}_2$ to form $1.20 \times 10^{24}$ molecules of HCl
C. $6.02 \times 10^{23}$ atoms of $\text{H}_2$ reacts with $6.02 \times 10^{23}$ atoms of $\text{Cl}_2$ to form $1.20 \times 10^{24}$ atoms of HCl.
D. 2 mole $\text{H}_2$ reacts with 2 moles $\text{Cl}_2$ to form 2 moles of HCl.
E. 1 gram $\text{H}_2$ produces 2g HCl.
APPENDIX D

LABORATORY SKILLS IN TITRATION CHECKLIST
LABORATORY SKILLS IN TITRATION

Name of Student:

A. SKILLS IN USING LAB EQUIPMENT

1. Skills displayed in the handling and reading of burette
   a) Rinses burette with solution to be used in it
      Yes — No —
   b) Reads the bottom of the meniscus
      Yes — No —
   c) Removes bubbles from lower end of burette
      Yes — No —

2. Skills displayed in the handling and reading of pipette
   a) Rinses pipette with solution to be used in it
      Yes — No —
   b) Reads the bottom of the meniscus
      Yes — No —
   c) Can pipette using mouth or pipette filler
      Yes — No —

B. SKILLS IN PERFORMING LAB TECHNIQUES

3. Does the student need help in setting up the experiment? Yes — No —

4. Is an indicator added to the solution before titration? Yes — No —

5. Is caution exercised near the endpoint? Yes — No —

6. Does the student overshoot the endpoint? Yes — No —

7. Is the flask constantly shaken during the titration? Yes — No —
8. Is a white background used to detect colour changes?  Yes — No —

9. Is the inside of the flask or beaker rinsed with distilled water during the titration? Yes — No —

10. Is the first titration regarded as final? Yes — No —

11. Are data recorded immediately after ratings are made? Yes — No —

12. To how many decimal places is the buret read? 2 — 1 — 0 —

13. To obtain volume of acid, student uses Pipet/Buret — Measuring Cylinder —

14. The indicator chosen for titration is pH — BTB — MO —

15. Container used for titration Conical Flask — Beaker —

16. Funnel used for transferring solution into buret Yes — No —
APPENDIX E

INTERVIEW PROCEDURE
GENERAL INTRODUCTION TO THE INTERVIEW

The interview begins with the following statement:

"I am ___________________ (interviewer states name). I am working on a research project at the University of British Columbia to gather information to be used in developing teaching strategies in chemistry. I am particularly interested in the understanding secondary school students' have on some of the concepts involved in volumetric analysis. Don't worry about your answer being wrong or right. I am interested in how you think about certain problems, so please answer as completely as you can. What you do will not be shown to anyone in your school, so it will not influence your grades. I need an accurate record of what we talk about and I can't possibly remember it all, so do you mind if I record our conversation? In addition, I will observe how you do the titration."

Problem Presentation

The subject was shown the required apparatus for the titration. The interviewer then proceeded as follows:

"You are given a known NaOH solution and an HCl solution of unknown concentration. I want you to find the volume of NaOH required to neutralize 25 ml of the base. I want you to show me how you might go about solving such a problem. Please do your calculations on the blank sheet."

The interviewer allows the subject sufficient time to proceed with the titration. As the subject goes through the titration, the interviewer asked for explanation of any procedural steps taken. Questions such as the following were asked:

"Why is an indicator needed for titration?"

"Why do you think this particular indicator is suitable for this reaction?"

"What is the pH of the acid and the base?"
What will be the pH at the endpoint?

What is the effect of added distilled water on the pH of the solution?

Do you know what an endpoint is in titration?"

At the same time, the manipulatory behaviour of the subjects was recorded. That is, whether they know how to use and read burettes and pipettes, what to do when they have almost reached the endpoint; whether they know what is involved in acid-base titration, etc.

After the subject has obtained the volume of acid needed, questions such as the following was asked:

"How can you obtain the concentration of the acid from the obtained data? In doing this I want you to verbalize the steps you use in your solution. Is the writing of reaction equation necessary for calculating the concentration of the acid? How did you get the number of moles of the base? What will be the molarity of the acid if the acid and base reacted in a ratio of 2:1 respectively? Given that the data remain the same, what will be the molarity of H2SO4 if it were used in the reaction against NaOH?, and What will be the molarity of HCl if Na2CO3 had been used in the reaction instead of NaOH?"
APPENDIX F

SUMMARY ITEM STATISTICS FOR

DIRECT PROPORTIONALITY SUBTEST
Summary Item Statistics for Direct Proportionality Subtest

Test Mean = 18.75  Standard Deviation = 4.07
Highest Score = 21.00  Lowest Score = 0.0
Reliability = 0.80  Standard error of measurement = 1.68
Number of Individuals = 378

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APPENDIX G

SUMMARY ITEM STATISTICS FOR

INVERSE PROPORTIONALITY SUBTEST
Summary Item Statistics for Inverse Proportionality Subtest

Test Mean = 13.92  Standard Deviation = 7.29
Highest Score = 21.00  Lowest Score = 0.0
Reliability = 0.93*  Standard error of measurement = 1.84
Number of Individuals = 378

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* The reliability of the total test (Cronbach's alpha = 0.50) suggests that the two tests should be treated separately. Examination of the correlation between the two tests (see Tables 10 and 16) supports this.
APPENDIX H

SUMMARY ITEM STATISTICS FOR

THE TOTAL TEST AND SUBTESTS OF

THE SUBCONCEPTS TEST
Summary Item Statistics for Subconcepts Tests

Total Test Statistic

Test Mean = 19.04  Standard Deviation = 4.91
Highest Score = 28.00  Lowest Score = 1.00
Reliability (Hoyt estimate) = .82
Standard Error of Measurement = 2.04
Number of Individuals = 379.0  Number of Items = 28.0
Reliability (Cronbach's alpha) = 0.78

Subtest A - Concentration

Subtest Mean = 3.14  Standard Deviation = 0.84
Highest Score = 4.00  Lowest Score = 0.0
Reliability = 0.43  Standard Error of Measurement = 0.57

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<td>4</td>
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Subtest B - Dilution

Subtest Mean = 2.28  Standard Deviation = 1.15
Highest Score = 4.00  Lowest Score = 0.0
Reliability = 0.55  Standard Error of Measurement = 0.67
### Subtest C - Stoichiometry

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<td>7</td>
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<td>8</td>
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Subtest Mean = 2.79  
Standard Deviation = 1.12  
Highest Score = 4.00  
Lowest Score = 0.0  
Reliability = 0.52  
Standard error of Measurement = 0.68

### Subtest D - Gram/Mole Conversion

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<tr>
<td>11</td>
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<tr>
<td>12</td>
<td>71.5</td>
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Subtest Mean = 3.30  
Standard Deviation = 0.92  
Highest Score = 4.00  
Lowest Score = 0.0  
Reliability = 0.45  
Standard error of Measurement = 0.59
Appendix 4 Continued...

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<td>16</td>
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**Subtest E - Mole**

Subtest Mean = 2.88  
Standard Deviation = 1.04  
Highest Score = 4.00  
Lowest Score = 0.0  
Reliability = 0.39  
Standard error of Measurement = 0.70

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<td>20</td>
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**Subtest F - Balancing of Equations**

Subtest Mean = 2.16  
Standard Deviation = 1.05  
Highest Score = 4.00  
Lowest Score = 0.0  
Reliability = 0.42  
Standard error of Measurement = 0.69
Appendix H Continued...

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Subtest G - Interpretation of Equations

Subtest Mean = 2.48  Standard Deviation = 1.26  
Highest Score = 4.00  Lowest Score = 0.0  
Reliability = 0.59  Standard error of Measurement = 0.70

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APPENDIX I

SUMMARY ITEM STATISTICS FOR

THE VOLUMETRIC ANALYSIS TEST
### Summary Item Statistics for the Volumetric Analysis Test

- **Test Mean** = 7.08
- **Standard Deviation** = 4.23
- **Highest Score** = 15.00
- **Lowest Score** = 0.0
- **Reliability** = 0.88
- **Standard error of Measurement** = 1.39
- **Number of Individuals** = 289

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APPENDIX J

MEAN AND STANDARD DEVIATION FOR THE
DIRECT PROPORTIONALITY, INVERSE PROPORTIONALITY,
SUBCONCEPTS AND VOLUMETRIC ANALYSIS TEST SCORES BY
CLASS, SEPARATELY AND COMBINED
Class Means and Standard Deviations of the Direct Proportionality, Inverse Proportionality, Subsumed Concepts and Volumetric Analysis Scores

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<td>1.701</td>
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<td>4.396</td>
<td>3.948</td>
<td>2.665</td>
</tr>
<tr>
<td>14</td>
<td>19.370</td>
<td>12.407</td>
<td>18.296</td>
<td>6.926</td>
<td>5.926</td>
</tr>
<tr>
<td></td>
<td>2.323</td>
<td>7.647</td>
<td>4.195</td>
<td>3.720</td>
<td>1.269</td>
</tr>
</tbody>
</table>

Continued...
Appendix J  Continued...

<table>
<thead>
<tr>
<th>Class</th>
<th>DP</th>
<th>IP</th>
<th>SCT</th>
<th>VAT</th>
<th>PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>18.989</td>
<td>14.325</td>
<td>19.366</td>
<td>7.192</td>
<td>4.113</td>
</tr>
<tr>
<td>Mean for Each Test</td>
<td>3.825</td>
<td>7.368</td>
<td>4.973</td>
<td>4.168</td>
<td>3.517</td>
</tr>
</tbody>
</table>
APPENDIX K

DATA FOR THE LABORATORY SKILLS

IN TITRATION INSTRUMENT
### Laboratory Skills in Titration

<table>
<thead>
<tr>
<th>A. Skills in Using Lab Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Skills displayed in the handling and reading of burette:</td>
</tr>
<tr>
<td>a) Inadequate</td>
</tr>
<tr>
<td>b) Adequate</td>
</tr>
<tr>
<td>c) Superior</td>
</tr>
<tr>
<td>2. Skills displayed in the handling and reading of pipette:</td>
</tr>
<tr>
<td>a) Inadequate</td>
</tr>
<tr>
<td>b) Adequate</td>
</tr>
<tr>
<td>c) Superior</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Skills in Performing Lab Techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>3. Does the student need help in setting up the experiment?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>4. Is an indicator added to the solution before titration?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>5. Is caution exercised near the endpoint?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>6. Does the student overshoot the endpoint?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>7. Is the flask constantly shaken during the titration?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>8. Is a white background used to detect colour changes?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>9. Is the inside of the flask or beaker rinsed with distilled water during the titration?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>10. Is the first titration regarded as final?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>11. Are data recorded immediately after readings are made?</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
<tr>
<td>12. To how many decimal places is the burette read?</td>
</tr>
<tr>
<td>a) 2</td>
</tr>
<tr>
<td>b) 1</td>
</tr>
<tr>
<td>c) 0</td>
</tr>
<tr>
<td>13. To obtain volume of acid student uses:</td>
</tr>
<tr>
<td>a) Pipette</td>
</tr>
<tr>
<td>b) Burette</td>
</tr>
<tr>
<td>c) Measuring cylinder</td>
</tr>
<tr>
<td>14. The indicator chosen for titration is:</td>
</tr>
<tr>
<td>a) Phenolphthalein</td>
</tr>
<tr>
<td>b) Bromthymol blue</td>
</tr>
<tr>
<td>c) Methyl orange</td>
</tr>
<tr>
<td>d) All 3 indicators</td>
</tr>
<tr>
<td>15. Container used for titration:</td>
</tr>
<tr>
<td>a) Conical flask</td>
</tr>
<tr>
<td>b) Beaker</td>
</tr>
<tr>
<td>16. Is funnel used for transferring solutions into burette:</td>
</tr>
<tr>
<td>a) Yes</td>
</tr>
<tr>
<td>b) No</td>
</tr>
</tbody>
</table>
APPENDIX L

INTERVIEW DATA FOR EACH INTERVIEW SUBJECT ON

CONCEPTS INVOLVED IN A TITRATION
Understanding of Concepts involved in Titration

pH and Concentration

Question:

1. The NaOH solution is 1M, what will be its pH?

Responses

A  The pH will be about 0.1 because concentration is 0.1
B  I don't know how to do this
C  We haven't been taught how to do this calculation in titration but I think it's 13.
D  13, pOH = 1, pH = 14 - pOH = 13
E  pH is log [H⁺], pOH = -log [OH⁻] and pH = 14-1 = 13
F  pH will be 10 no it will be 13 because pH + pOH = 14 and pOH is 1 so pH has to be 13
G  About 10; strong base is 14 so I figure it will be 10
H  pOH = -log [OH⁻]; pH = 14-pOH = 13
I  13 because concentration is 1M and pOH is 1 and pH = 14-1 = 13
J  I don't know
K  If it was 1 the pH will be 0. pOH = -log [OH⁻] = 1, pH = 13
L  13 (student shows calculations)
M  pOH = -log [OH⁻] = 1, pH = 13
N  pH will be 11, no 13 since pOH = 1 and pH = 14-1 = 13
O  I don't know
P  13 (student shows calculations)
Q  13 (student shows calculations)
R  I don't know
S  13 (student shows calculations)
T It will be $10^{-14}$ because there's as much OH as possible in the solution. In water they are equal $10^{-14}$ but I think that's what it will be. 14 is the maximum pH.

U It will be 13 (Student shows calculations)

V 13 (Student shows calculations)

W 13 (Student shows calculations)

X It's going to be 7

Y It will be 13 because it will be negative log of concentration of base and then $14 - pOH$

Z (The pH of) the NaOH will be 13, ... the negative log (of $H^+$ ion concentration) is the pH and pH + pOH add up to 14.

AA It's 13 because you use negative log of concentration and this gives you pOH which is one and pH = $14 - pOH$, so it's 13.

BB You have to get ... what do you call that base concept. The equation of $X^2 = .1 - X$. ... roughly, it will be 7 or 8

CC 13, concentration is $1 \times 10^{-1}$ and negative log will give pOH and pH = $14 - pOH$.

DD pOH is equal to $- \log 1.0 \times 10^{-1}$ and we get the pOH is equal to 1 and if we want to know the pH value we can use 14 subtract 1 and we get 13.

EE It will be pH of 1 (because) O.K. you first change it to scientific notation which is $1 \times 10^{-1}$ and you take negative log of that which is 1.

FF (Student asks for $K_b$ and uses equilibrium constant equation to find pH) pH is 13.

GG (Student asks for dissociation constant of base to find the pH) The antilog of the dissociation constant (1.00) and this gives the pOH and then I use $14 - pOH$ and gives the pH of 13.

HH pOH = $-\log$ of concentration, pOH = 1.80 pH = 13

II Yeah that's what I am not sure of. I don't know how to find it.

JJ pH will be 13, pOH is 1 and pH = $14 - 1 = 13$

KK It's $10^{-2}$ and if you take the log of $10^{-2}$ you get 2
LL One, no that's pOH ... 14 minus pOH is 13

MM The pH will be 13. If it were acid it's pH will be 1 but because it's base that will its pOH and so that means its pH has to be 13

NN The pH will be 13, negative log of concentration, the pOH will be 1 and then subtract the 1 from 14 to give me 13

OO It will be 13 because .... you'll have OH⁻ ion concentration to be .1M because it's a strong base .... When you find the pOH which is the negative log of OH⁻ concentration you'll have 1 and then to find the pH you take PKw which is 14 and you subtract from it pOH and that gives you 13

PP pH will be 13 because ... you take the pOH by taking negative log of 0.1. Since it's a strong base and it dissociates 100% into OH⁻ and Na⁺. And pOH + pH = 14 and so pOH is 1 and therefore pH = 13.

QQ It will be 1 ... no, the base isn't 1, it will be 13 because pOH is 1

RR It will be the negative log of its concentration so it will be negative log of 0.1, so it will be 1

SS pH will be 1

TT pH is 13

UU pH is 13 for sodium hydroxide. The NaOH concentration is equal to the OH⁻ concentration. You got 0.1M NaOH so you get 0.1M OH⁻ and then I just want H⁺ concentration. [H⁺] x [OH⁻] 10⁻¹⁴ and OH⁻ is 0.1 therefore 14 divided by 0.1 and you get 10⁻¹³ and pH = 13.
Question:
2. If the HCl is also 0.1M what will be its pH?

Responses
A  I am not sure but it will be about 0.1
B  No, I don't know
C  It's the negative log of hydrogen ion concentration but I can't calculate it. The pH will be 1
D  One
E  pH will be 1
F  pH = -log 10^{-1} = 1
G  I don't know
H  pH = -log of concentration .'. pH = 1
I  I have to find the Ka for HCl .. no, pH is hydrogen ion concentration. It has to be 1
J  I don't know
K  One
L  One
M  It will be 1
N  One
O  I don't know
P  One
Q  Yes it should also be 13 ... no the pOH = 13 and pH = 1
R  I know it's negative log of hydrogen ion concentration but I can't remember
S  One
T  The HCl will be about 1 ... One is the highest for an acid
U  HCl is 0.1M so it's one
V  One
It will be 1

It will be 7

It will also be 1

It will be 1

Then that will be 1

About 3 or 4 (Student does not explain why)

One, yeah one. Concentration will be $1 \times 10^{-1}$ and negative log of that is one

Conc. of HCl is just equal to concentration of $H^+$ ions and so .... We can just take $-\log$ of $1.0 \times 10^{-1}$ and we get the pH value is equal to 1.

Should be the same, pH of 1

(Student asks for $K_a$ and uses equilibrium equation to calculate pH) one

(Student asks for dissociation constant of HCl) The pH will be antilog of the dissociation constant which will be 1

One

I don't know

1

0.1 because HCl dissociates 100%, therefore the $OH^-$ ions equals that of the HCl so HCl is 0.1 ... I don't know

Then it will be 1

1

pH will be 1

It will be 1

1

The acid will be one if it is 0.1

It will be 1, no ... I guess it will be 1

If the acid were .1 molar, then the pH will also be 1

Negative log of concentration ... pH is one, yeah just one

The pH will be 1
Question:

3. You used 25 ml of acid from stock solution. Do you think the 25 ml taken out from the stock solution will affect the conc. of the remaining stock solution? Why?

Responses:

A  The conc. will stay the same because you're not taking out anything. The conc. is all the same throughout

B  It won't affect the concentration because it's an already made up solution and it doesn't affect the concentration

C  It should be the same since it's even

D  It stays the same because there's same concentration of HCl for the entire solution

E  It will stay the same

F  It will remain the same. It's all the same

G  There's different amount of moles but concentration does not change because the volume also changes

H  Nothing will happen; It's all got the same amount of molarity or concentration. There will be less mole but there will be also less volume so concentration will be the same

I  Concentration will be the same because I'm not adding anymore acid

J  No there won't be any affect, the concentration is the same

K  The concentration will be the same throughout

L  It remains the same. It is the same solution

M  No, I don't think it will affect it. I am taking equal proportion of acid and water so concentration won't change

N  It will remain the same. Every part is the same

O  It won't, it's the same concentration

P  It doesn't change because anything you take out (of) there the concentration will be the same
Q Concentration will be the same; the number of moles will be different but the volume is also different so it (concentration) is the same

R No it won't affect the concentration. It's all even

S It's always the same

T Concentration will stay the same because you're not adding any more acid

U No it won't affect the concentration because it's throughout. It should be all even

V No, because there's a certain number of molecules per litre so like when I take it out there's still the same amount per litre

W No, I am not sure ... It will be the same because the HCl and the water I assume they've been standing there for a while and so the HCl can diffuse throughout the water unless it settles out but I don't think so

X No, not at all; it won't affect it, no. It's the same solution. It has the same concentration

Y The concentration will stay the same because even though you take some of the moles of HCl, the volume will decrease proportionately

Z No, because it's all supposed to be stock solution and it doesn't change when you take some

AA It doesn't, it's the same (because) it's diluted to a certain concentration; no matter what volume you take off the concentration, will still remain the same

BB No, (but) I don't know why

CC Oh no; ... well (because) concentration of hydronium ions is constant throughout the whole stock solution so it won't matter

DD I don't think so (that it will affect it) ... because the concentration of the solution is constant, right, ... If we take out a certain amount of the solution, it doesn't affect the concentration of the solution

EE No, it should be the same because it's already been mixed up. O.K. ... There was certain amount of volume and certain moles of the solid was added to it to make that molarity. So it should be the same
FF The concentration of this (acid in beaker) and this (acid in stock) are the same so the concentration will be the same ... You only took part of it; It should be the same. It's the same solution

GG Yeah, I think it won't affect the concentration of this acid. I think if it don't affect the concentration of this acid, it's because the volume is decreased. If I put 10 ml in here (beaker), the volume in here (stock) is decreased and moles is decreased so that means the concentration here (stock) is constant.

HH Oh, it won't; the concentration will remain the same. The concentration is just moles per volume. If I take certain volume, I will take in proportion the number of moles so if I take 10 ml, I take thenumber of moles in proportion

II No, it should not because we removed it from the (stock) solution and we did not contaminate the stock solution and therefore theoretically this (remaining stock solution) should remain whatever it is and if we use some in the experiment it (concentration) should not be altered because concentration of this (stock) per litre is always set; even set (same) in here (referring to acid in beaker)

JJ It will not affect concentration of remaining stock solution because you took so many moles out, right? and you took certain volume of water out, and the remaining number of moles will be the same for the volume here (remaining stock solution) right. The ratios are the same

KK No, because you just decreasing the volume but that doesn't change the concentration. No it's still the same amount of moles per litre even though the volume changed so concentration should remain the same.

LL The concentration of this (remaining stock solution) should be the same as the original (because) well, I didn't dilute it with anything else. I mean there's no reason for it to go down other than may be that the beaker is damp

MM No, because the concentration is the ratio of the amount of acid per volume. So if you take out a volume you're also taking out acid and so it will always stay the same.

NN No, because it's not changing the ratio of the moles to volume of liquid

OO It will be the same. The concentration is set. Like I can add H₂O to it and concentration won't change because H₂O doesn't affect it because it's something to do with, I think, the Ka value - it's too low or something
No because if you have so many molar solution here (stock solution), then you gonna have so many moles per volume here (stock solution). When you take it (25 ml) out you taking out certain amount of moles with a certain amount of volume so you taking out the same concentration as in there (stock solution) and the concentration shouldn't change. You not just taking out moles and you not just taking out water, you taking out both so the concentration will stay the same.

No, because it's all the same concentration throughout the whole acid.

No, the concentration will be the same, because it's a standard solution, so it should remain constant. I am not sure.

No, the concentration will be the same because this (the remaining solution) is still a certain amount of moles per litre or whatever and you've just taken a certain amount out (so) it won't change the concentration.

No because concentration is constant throughout.

No the concentration will be the same because there's the same number of moles per litre in there.
Question:
4. Will the volume taken from the stock solution affect the number of moles of acid in the remaining stock solution? Why?

Responses:
A  The number of moles will decrease because you're taking a certain amount of mole out of it
B  No, it won't because it's the same solution
C  It will be less. You have less volume
D  Yes, because you taking some out of it so it's less, small
E  It will decrease. I think so. The volume will be less
F  It will be the same because the amount will be the same
G  It does change, decrease ... because you're taking some amount out
H  There will be less mole (since) there will be less volume. But concentration will be the same so moles will decrease
I  Number of moles in stock will decrease (since) I'm taking 25 ml for the titration
J  No, the moles is the same throughout
K  The number of moles is equal to how much you have - the volume, (multiplied) by the concentration; the concentration is the same, the volume changes so the number of moles will change
L  No, that stays the same too. It's the same solution
M  Yes, the total number of moles because I'm taking some out
N  It's got to be different in the number of moles because it's a different volume now
O  I don't think so (because) if it's the same concentration then the moles are the same
P  It doesn't change. I am not quite sure of that one
Q  The number of moles of acid will be less but the volume is also different so to compensate the concentration you have to make the moles different
R Yeah, it will reduce it because to find moles you have to use the volume and if the volume is small then the moles you're going to have will be small too.

S Of course it will decrease since you taking some out.

T (It will) stay the same because you're not adding anything.

U Yes it should be less (because) when you have moles per litre you have a certain moles per one litre and if you take say one-tenth of a litre then you're taking one-tenth of that mole. I am not sure whether it makes sense to you but it makes sense to me.

V Well, it's still the same because still we started off with the same solution so you not adding any more water or anything so you not diluting the solution. It's still the same amount of moles because it's still the same solution.

W I think it will be less number of moles. I took some out but I don't think it will be less moles per litre.

X Yeah, it should. It should be less (because) you'll be taking out some of the acid.

Y Yes it will (because) you take 25 ml so you have less moles of HCl in there (stock).

Z That will change, because you have different quantity of acid.

AA I think it should remain the same because if the concentration doesn't change, right, then no matter how much you take out the moles will stay the same.

BB No because it's the same concentration so it (moles) won't change.

CC Yeah, you take out some so it will decrease.

DD Yeah, ... the moles will be decreased. From the equation mole is equal to molarity times volume, right, and if the volume changes then the moles change. Because the molarity is constant right, so moles is directly proportional to the volume. Is that right?

EE It will be a little less but then it varies with I guess the volume too because you've taken some of the water out there so you lose some of the grams of the salt dissolved in it.

FF The same. If this (acid in beaker) is one mole this (acid in stock) will be one mole too. If you think about, regardless of how much you take, moles should be the same.
GG  I think the moles will be less when you take some out

HH  It will decrease but then so is the volume so the concentration will be the same (The moles) will decrease because I pour 10 ml off

II  Well as long as we take it out it will vary because you have the number of moles inside here (stock solution) decreased. It's not moles per litre which is like a constant

JJ  Yeah, the moles will be less because if you took 10 ml of 0.1M so it will be .001 moles less than original stock

KK  It will be less moles but the same moles per litre because you taking some of it away

LL  The concentration is the same so the amount of moles per total volume is the same but ... if that (original stock solution) was filled with ... 1 mole of material in here (remaining stock solution), it's only going to be actually half a mole in a half a volume if you take half the solution, so the concentration is the same but there's less of the material together

MM  That will go down because you're taking some out so there will be less moles

NN  It's gone down because if you're taking some out then the number of moles in the solution is less because you're taking some out

OO  It stays fairly constant because if you're removing the liquid from it, like I will be removing moles definitely from it but I'll also be removing the liquid so I guess it will go down in a 1:1 ratio. So it should stay the same

PP  Yeah, the moles will decrease. Some part of the moles will be taken out but you also taking out some of the volume so the concentration level stays the same. Because you taking out part of the solution, there's certain amount of moles in there so when you taking out the solution you also taking out part of the moles - that is, a fraction of what was in there (stock)

QQ  Oh, that will go down (because) well, you took some of it out

RR  It stays the same ... I am not sure why?

SS  Oh, the number of moles in there ... oh, it won't change either (because) well if you take some of it out you still going to have a certain number of moles per litre or per whatever you have left
Number of moles per litre will not be affected but the amount of moles will be affected. It's like saying if you have 5 grams and you took off 1 gram, the number of grams will be affected.

No, it won't affect it (I don't know why).
Question:
5. As you're adding NaOH to the acid in the flask, what do you think happens to the pH of the solution in the flask?

Responses:
A. The pH will go down because the pH for high acid is 14, neutral is 7 so it's going down to neutral and in base it will go down below 7
B. It will probably go down
C. It increases
D. The pH will increase so that it will be more basic
E. There will be a small change upward
F. It will increase
G. The pH increases
H. The pH goes up because the concentration goes down
I. It rises
J. It increases
K. The concentration changes slightly upward
L. I think it will be lowered a bit .... it will be a little more basic, may be not that much since you still have excess acid
M. It changes slowly at the beginning becoming more basic
N. It's gonna be more, a slight increase
O. It will be lower
P. It goes up a little
Q. It will become less acidic. The pH will increase
R. The pH will stay the same because if you add enough it will decrease
S. The pH will go higher
T. The pH goes up because $H^+$ ion is combining with the $OH^-$ ion and form water and so that you're taking the $H^+$ out of the solution
It starts going up. It's probably one then it should start going up to 7 and when it reaches 7 it should be neutralized.

It's going down ... oh, it's going higher because you're adding some base which will neutralize the acid so there's less hydrogen ion in solution so the pH will go up.

The pH of the acid is getting closer to 7; it's increasing because more of the H² ions from the acid combine with OH⁻ from the base so there's less H⁺ ions in solution so the concentration is less.

The pH is gonna go up; sooner or later it's going to be 7.

The pH will increase because the reaction between the base and acid will lessen the amount of free hydronium ions.

The pH becomes more basic, it becomes higher.

I think it (the pH) rises. Maybe it's because the pH of the base is high, right, and if you add it to a low pH it should rise until it's neutral.

It will go higher towards the basic.

Actually it increases the pH but decreases the concentration of hydronium ions.

.... It may be 7, (because) 7 is the neutral point. That is, it will go up.

It slowly increases and neutralizes at 7.

.... O.K. in the beginning we have pH1 and there's no base yet; therefore if we add more base, there gonna be more and more base but the pH should be negligible and therefore pH of base will be .... It will decrease, no, no, the pH will always be the same even though you add the base. You just gonna have more base, that's all, no more pH. The pH will still be 1.

It will increase the pH.

If I add the base, then there'll be less hydrogen so pH should decrease. Yeah, it will decrease ... (Interviewer asks student if decrease means it will go to zero) ... Yeah, it's decreasing that means, the number of hydrogen ions is decreasing.
The pH will decrease because the hydrogen ion is being used in this reaction. From what I see ... there's a certain pH in here (beaker); there's a certain amount of hydrogen ions and as it mix with a certain pOH that the two together combine to form water and salt and what happens is that the pH decreases ... The pH will decrease because the $H^+$ ions will decrease.

It increases till it gets to 7

It should increase

It goes up because you're diluting it ... because the pH of the base is high, the acid is lower so they combine

It goes up

It goes up towards pH 14

The pH of the acid is gonna increase

It goes up

It goes down ... No, it doesn't go down, I think it increases because as you add the base the Na$^+$ ion doesn't react but the hydronium ions take away the hydrogen in the acid

It should rise

It's increasing

The pH will go up

As I add the base the pH will go from 1 to 2 to 3 and so on
Question:

6. How does the pH change in the early part of the titration compare to the change near the stoichiometric point?

Responses:

A  Evidently I figured it will be a lot slower near the end because only few ions of H\(^+\) will remain

B  There will be a rapid change at the beginning because there's more acid in the flask at the beginning

C  It will be the same

D  I don't think it's going to be the same. I think it's going to be slow at the beginning and fast near the neutralization point which is 7. I can't really tell you exactly why but I think at the beginning you're adding a little bit of base to acid and if you add more you have a higher concentration of OH\(^-\) than H\(^+\) so the pH will change faster

E  It is faster near the stoichiometric point. It really comes straight up (as this graph shows); I don't know (why)

F  The change near the equivalence point will be smaller because there will be few H\(^+\) ions

G  When you look at the titration curve it shoots right up so there's going to be a rapid change

H  Well at the beginning it is a slower change and then it gets more reacted and if you get on to the equivalence point that's when the graph is nearly vertical

I  Since there are more H\(^+\) ions at the beginning, the reaction will be easier at the beginning than at the end so there will be a rapid change in pH at the beginning but it will slow down near the end

J  It will be different, there will be a larger difference in pH (near the endpoint) because near the endpoint the solution is almost neutralized and a bit of base will almost rapidly change the molarity and pH

K  It will change greatly near the equivalence point (because) you have fewer H\(^+\) ions

L  Probably just the same change except you can see it (colour) now
M It changes slowly at the beginning but shoots up when it gets nearer the equivalence point. This is shown in this graph (of pH against volume of base added).

N It will be greater near the endpoint because there will be a small amount of H\(^+\) ion remaining.

O I don't know.

P pH will jump high near the endpoint. There's less H\(^+\) to react with the same volume of OH\(^-\).

Q The rate (of pH change) will increase greater toward the end because at that point you'll have less H\(^+\) ions in the acid but you're putting the same OH\(^-\) ions therefore there's more OH\(^-\) ions as compared to H\(^+\) ions each time you put base in.

R It will decrease by the same pH. It's the same change for each drop.

S The change is the same but it's the indicator, the colour of the indicator that changes rapidly.

T (Near the stoichiometric point) it's (pH) gonna level off. It will stay level for a while and then rises again.

U I will say that it's the same at the beginning as it is near the end. No matter how much you put in it still gonna go up at the same rate.

V It will be the same; it must be because they react the same way so it doesn't matter when you added the drop so the pH should go up steadily.

W I think it will be greater near the end because in the beginning there's a lot of H\(^+\) ions and the concentration is say 10\(^{-1}\), then if I add just a little bit of OH\(^-\), suppose .0001 then I will still have .9999 for the mole of H\(^+\) but if I have added for a while till I get to the point where I have .0001 moles H\(^+\) and I add a drop of OH\(^-\) that has .0001 then they neutralize each other and you have no more H\(^+\), so here (near the end) you've added these (.0001 moles H\(^+\) and .0001 OH\(^-\)); it's a 100 percent while here (at the beginning) it's one tenth of a percent so you not changing it much.

X Well, you have more hydrogen that's going to be removed so I think the pH will become more basic. It will be higher than 7. Actually initially, I don't think it will change the pH because you're trying to figure out what the pH is so if you keep adding you just gonna keep changing the pH the same way.

Y They (the pH change) will be the same for the rate of change (near the stoichiometric point and at the beginning) if you added drop by drop.
Z The change will be rapid in the beginning (because) when it approaches the endpoint it starts to slow down because it's getting to the endpoint ... there's few $H^+$ ions ... I don't know

AA I think it increases evenly throughout the whole experiment as you add the base ... I don't know (why)

BB I don't think so. It will start off slowly and gradually get faster (because) it takes time to react. There's greater amount of $H^+$ ions at the start

CC I think it will be the same or roughly the same (because) so many $OH^-$ will neutralize so many $H^+$ ions and as long as you take this much (volume) of acid and next you take so much (volume) of base until you hit that endpoint the pH will increase linearly

DD I think the first one (initial stages of titration) will be faster ... because NaOH and HCl are in forms of ions in solution, right?; When we mix them together they react easily because they are free ions and the chance of collision of the ions is very high (at the beginning) so it's very easy to react

EE I think it does increase evenly because we're not dumping a large amount of base into your acid to change the pH level. You're slowly titrating it dropwise so it will change slowly throughout

FF I don't know

GG I think if I add the first drop of NaOH, the pH will increase faster than when I add the last drop because at the beginning the NaOH reacts completely with HCl. The first drop will react completely with HCl because there's more $OH^-$ and then may be up to 100 drops the reaction ... may be (with) the 100 drops only 70% react with HCl. Therefore it will be slow at the end

HH (Student indicates that near the endpoint, there'll be no more protons so the pH will be zero). The decrease will be the same way if you add the same drops

II (Student indicates that near the endpoint the pH will be very very low such that when you reach the endpoint there will be very little pH left; that is it will decrease). I am not sure, I don't know

JJ It will be the same steady change because you're adding base to an acid in the same way so it will change evenly

KK There will be different rates. In the beginning it will go quite slow and at the end you have a large increase. I don't know why but we did a graph and that's the way it went
It increases very rapidly near the endpoint. Well, initially there’s a lot of $H^+$ ions here (acid in flask) ... but as the hydrogen concentration decreases as you add more and more base, each drop begins to really affect the amount of hydrogen, the concentration. It's a logarithmic S-shaped type of problem.

I think it starts out slowly at the bottom (student refers to a graph of pH against volume of added base) and then go up steeply and then level off slowly at the top. (This is because) well, you start off adding, let's say half millilitres of base to begin with but it doesn't make much difference but when you've already got say, 8 ml base in there and then you add another half millilitre, it's gonna make a large difference in proportion to the amount of acid that's left and so it will go up more.

I'll say it will be the same throughout because it's not a buffer. We haven't drawn up the graph for strong acid-strong base. But it just seems that each drop of $OH^-$ has the same number of moles and each number of miles will neutralize the same amount of acid.

As you near the stoichiometric point where the number of moles is equal and as you go drop by drop from there the pH climbs more rapidly. I guess it's because as you're adding base, the concentration of your acid is changing so your number of hydronium ions that are left in the original acid will be used up so then as you add more of the strong base each drop will be consuming more and more of that because there'll be less and less left as you go along so that will cause the pH to change more rapidly.

O.K. it's slower at the beginning because ... It's just that you consume most of the acid in there and you only got a small bit left to do (near the endpoint). And therefore as you're taking away the $H^+$ ions, you're increasing the pH but right near the end you're consuming almost all of them which tends to make the pH jump rapidly.

It changes rapidly as you approach the endpoint, I believe because the concentration of the HCl got quite smaller and (so) it's very easy to vary it ... that is, if I add more of the NaOH, it takes a lot of the $H^+$ ions out of the solution by turning it back to water and the reaction just continues to proceed until all is gone. I think that's all.

There should be a major leap, a major increase (in pH) near the stoichiometric point because at that point there is the same amount of HCl and NaOH so I guess because of this the equal moles react so as to change the pH quickly.
SS After you hit the titration point ... the stoichiometric point and the last drop that you add, the pH increases rapidly ... Like if in the beginning as you add (the base) it (the pH change) will probably be quite constant to a certain point, then after a certain point it goes ... increases ... rapid increase because you are coming closer to the endpoint.

TT In the beginning it will be slower and then there will be a fast rate. So if you can draw a graph it should go slowly and then level up and goes up because it means (near the endpoint) you are ... I can't remember.

UU ... The pH will change uniformly probably and then near the stoichiometric point, it will jump, ... I think because ... Oh, I am sorry, I can't explain.
Question:
7. What will be the pH at the point when there are equal amounts of acid and base?

Responses:
A  7, water will be formed and water has pH of 7
B  4, the pH will be 4
C  7, when they react completely
D  7
E  Around 7, I think
F  Around 7
G  7
H  It will be 7 if it's a complete and total reaction, that's the neutral point
I  Around 7
J  pH is 7
K  It will be 7
L  7, I think
M  7
N  7
O  7 because it's neutral
P  7, I am not quite sure
Q  7
R  It's 7
S  The pH will be 7
T  pH is 7
U  If it were perfect it will be pH of 7
V  It should be when it is neutralized, it should be 7
W  7
X  Somewhere around 7, very close to 7
Y  The pH will be 7
Z  Neutral (pH of 7)
AA It should be you're getting a neutral salt so the pH will be 7
BB About 7 (It has to be about 7 because 7 is neutral, right?)
CC 7
DD If they react completely the pH will be 7
EE It should be around 7
FF It will be a little less than the (pH of the) base, less than 13. One, I think
GG It will be 7 because they are both strong base and acid
HH It will be 7 because if it reacts completely, then it will be neutral, neutral is 7
II It will be very low, almost obliterated I would imagine because they will form this salt and water (student points to reaction equation). And water has very low dissociation and it has very low concentration of H\(^+\). For our purposes right now, they tell us that it is zero especially the distilled water because it's such low concentration of H\(^+\) ions
JJ It will be 7
KK Below 7, about 4.7 because if you take the ratio of the concentration of your base to your acid times the Kb value, it will come out to be that
LL 8 or 9 somewhere in there. Well, it's gonna be above 7. If they are exactly same amount then the pH is 7 and then if they hydrolyze it will be 7. If you have strong acid and strong base, when you have equal amounts the pH will be the pH of water so it will be 7
MM O.K. it will be 7 because they are both strong so they will react evenly and then all that you have left is water and the water has pH of 7
NN pH 7
OO It should be 1:1. I think it should have a pH of 7 because HCl is technically strong acid and totally dissociated. NaOH is totally dissociated because it's a strong base ...
PP  7

QQ pH will be 7

RR It should be above 7, ... I can't remember, it is around 3, that's when HCl reacts with NaOH you get a pH of 3

SS Neutral, 7; 7.6 or 7 because that's when you have equal amounts of each, right

TT About 7 because 7 is the neutral point

UU pH will be 7
Question:
8. When you overshoot the endpoint what will the pH be?

Responses:
A  It will be lower than 7
B  It goes past neutralization and makes it more basic
C  It becomes more basic
D  More basic so it's going to be higher than 7
E  It would be over 8 since this (phenolphthalein) changes colour from pH 8.2 - 10
F  It goes up since you added more base
G  It becomes basic
H  The pH will be higher but the change is slow again
I  It will increase. The pH will be above 7
J  More than 8
K  Nothing happens to the pH because it only takes so much. But it screws your calculation
L  The pH will be lower than 7
M  A bit more basic
N  It will increase you're adding excess NaOH
O  The pH will go down because you're adding more base
P  (It becomes) more basic ... more than 7
Q  That means you'll be adding more base and the pH will increase. It will be greater than 7
R  If you add more base then it will turn blue and pH will go down. If you add more acid pH will go up because there will be more acid
S  Of course the pH will go up. You're adding more base
T  The pH will go up if the OH⁻ ions increase
U  Then the solution will keep on becoming more basic and as you continue adding base it will just become pH of 14
V  It becomes basic, higher than 7
W  It will have a basic pH, over 7
X  It becomes more basic, over 7
Y  It will be higher because there's more hydroxyl ions
Z  It will become clear again; the pH will become more basic; the solution will be basic and pH will increase
AA It will remain the same (because) if you adding NaOH then you're adding more OH\(^-\) into the solution. I think it won't change because you only have an excess of OH\(^-\) and no hydrogen to react
BB  It will go higher
CC  It will keep rising
DD  It will go higher and higher
EE  It increases
FF  The pH will stay the same, pH of 1, even though you're adding more (base)
GG  I think it will still increase
HH  I'll say the pH will be just the same as this (student points to NaOH) because if you just keep adding base, then it's just like adding this base to water
II  Oh, I don't imagine it (addition of excess base) will affect it (pH). It will just mean that perhaps this was a different equation (student points to reaction equation)
JJ  It will become more basic
KK  It would increase, probably above the stoichiometric point
LL  The pH goes up and then sort of levels off after a while
MM  It will be going up
NN  It will rise to 1.4
OO  The pH increases again but not at a rapid rate
PP  pH will go up
QQ  It will increase
RR  It should remain constant or it should remain at the same level, it shouldn't vary

SS  It gets redder and redder ... the pH will increase

TT  The pH will keep on rising

UU  Oh, the pH will increase
Question:
9. If during the titration distilled H₂O is used to flush down the acid on the sides of the flask, what effect will this water have on the concentration of the acid in the flask?

Responses:
A  I think it will lower the concentration of acid since the volume will be greater
B  It will decrease the concentration because volume will increase
C  The concentration will decrease (since) the volume of the solution is greater
D  It will change the concentration, it will decrease (because) there's more volume
E  It will decrease the concentration because of the volume
F  Nothing, the concentration doesn't change. It's just water
G  It becomes less concentrated because you're adding more water
H  That will affect the concentration because you have the same amount of moles in a bigger volume so the concentration will go down
I  It will affect the concentration of H⁺ ions. It will be diluted
J  No it won't affect the concentration. Water can't. It would be the same
K  Not that very great ... I really don't think so. It won't affect it because it's just water
L  I guess it will change (decrease) if you're adding more water
M  It will affect the concentration in there because you're diluting it but the moles stay the same
N  It will dilute the acid so concentration will decrease
O  No, it doesn't affect it water is neutral
No it won't have any effect. The pH (of water) will be 7 but if you added some other water like tap water it will affect it because you have different substances in it

The concentration will be less. You're adding more H₂O and volume will be more

I suppose it might because if you add water it affects the concentration. The volume will be more

It will decrease the concentration because you're diluting

It will (increase) because the H⁺ from HCl will combine with the OH⁻ ion of the water that is dissociating some what. And therefore it will shift the equilibrium of the whole system. That is HCl → H⁺ Cl⁻; HOH → OH⁻ + H⁺. So that when it shifts, the equilibrium of this (HOH) will tend to move this way (to the right) more. That means the H⁺ ion will actually be increasing so there will be more in the whole system. So it will actually affect it a little bit

No effect, because ... I think there's a logical answer but I don't know

It will dilute it so concentration will be less ... the volume will increase

It will dilute it. The concentration will go down, that's a lower concentration

Definitely it should decrease because you get more hydrogen ion (from H₂O) so you gonna form more water. It's gonna dilute it

The concentration will decrease ... because there's more volume

It will decrease the concentration (because) you're diluting it, adding more water.

No, I don't think it will affect it. It's just water

It will be weaker -- it will decrease because it will be diluted by the water ... the volume will be greater when you add the water

I assume it will decrease it because you're having a larger volume for so many amount but there was something I read a few days ago that somehow it does not decrease. I will assume it will decrease ... I think it (the book) was wrong

It will dilute the acid, make the volume greater, it means the concentration of the acid will be decreased
EE It will dilute the acid a bit. The concentration will be low. There'll be less moles of the solid compared to your liquid.

FF Yes, it will have an effect—the volume will increase and it will lessen the concentration of the acid.

GG Yeah, because concentration as opposed to mole is... 4 the molarity of this acid is 0.5. If I take 10 ml, the mole in here (beaker) may be 0.005 mole. But if I add the H₂O in here (beaker); If I add maybe 90 ml of H₂O in here (beaker) the concentration will be 0.005 moles per litre... It will affect the concentration of the acid but it will not affect the number of moles.

HH Yeah, it will affect it because water is changing the volume but it does not matter because I know it's (volume)... 25 ml in there, so it doesn't matter if I add water after that.

II The concentration will change because... what we did here is pour that (acid) straight into here (beaker). When we add water to it we're increasing the volume and decreasing the concentration because what you saying is how many HCl molecules you have for so many litres, that's what molarity is defined...

JJ It will affect the concentration (because) you're diluting it.

KK No, it won't (have any effect) because... Yeah the concentration will be less... because the HCl molecules are more spread out in the water and there'll be fewer moles per volume.

LL The whole volume increases, well, the amount of moles to volume is diluted so the concentration will decrease.

MM Yeah, well, because you're adding water so it's gonna be diluting so the concentration will be lower—the volume will increase.

NN It will lower the concentration because you're increasing the volume without increasing the number of moles.

OO No because water doesn't come into (calculation of) concentration. When you add water to it and find the concentration, the concentration won't change because it doesn't react with the acid.

PP Yeah, it will, because concentration is given to you in moles per litre... When you add more water you're increasing the volume but you not decreasing the acidity of the solution, therefore you have the same moles of H⁺ ions and chloride ions. You're increasing the volume so the concentration goes down.
QQ This will affect the acid concentration. It will make the concentration smaller if you add more water because the volume will be bigger.

RR It will make it decrease because you are adding larger volume. The moles will stay constant but the volume is increased so it should decrease.

SS It will be diluting so it (the concentration) will be less because you have less moles per volume. That is, before, if you have a certain moles per volume and you add more water to the solution, you have more water but less moles originally so you have less moles per volume right now.

TT Yes, when you are adding water you're adding more OH⁻ so you have more base. So the concentration of the acid will go down.

UU I don't think it will have any effect (because) ... Sorry I can't answer that (i.e. why it won't have any effect). Oh, no for the concentration I think it will affect the concentration. I think because you are adding more volume to it so the total concentration will be ... less; It will decrease.
Question:

10. How will the added water affect the number of moles of acid in the flask?

Responses:

A  Number of moles will stay the same because there's still the same amount of HCl in there

B  Probably the number of moles will be affected too (i.e. decrease) because concentration is decreased

C  No, assuming there's no moles of HCl in the distilled water that you're adding that is, it is neutral, the number of moles of HCl that were originally there will remain the same

D  It won't change because you still got the same number in there. You're not adding anymore HCl or NaOH in the water

E  It will stay the same because you're not adding any more HCl except for just a small amount of H⁺ that's in the water but that's pretty small

F  It will be the same. There's no acid in the water

G  The same number of moles of acid just that it's less concentrated. The water does not affect the amount

H  The number of moles won't change unless you add something that takes the moles away

I  It should be the same because I think if it's distilled water then the moles will be the same ... distilled water is neutral

J  I don't think it will affect the moles. It will be the same. Water doesn't affect it

K  I don't think it should. Hold it I remember we did that when there were solids sticking to the sides. It shouldn't; it doesn't affect the concentration or the number of moles. It (water) is always neutral

L  The number of moles will be the same. The water won't change it

M  It will affect the concentration but it won't affect the actual amount of acid and that's what I'm interested in. But also, the volume will increase and that make it (moles) stay the same
N. It will stay the same. You're not removing the HCl by adding H₂O.

O. No I don't think so. I think it's just the same acid.

P. I don't think it changes. Water is neutral so you add and it stays neutral.

Q. The number of moles will be same as we started with. Water doesn't change it.

R. Yeah, I think it would decrease. Since it affects the concentration so indirectly it may change the moles.

S. It will remain the same because water is neutral.

T. It will decrease because it will be smaller in concentration because there's more water and it will be less.

U. No it won't affect it. It's a memory question ... I forget why.

V. It will be the same. You're not adding acid.

W. Number of moles will stay the same because you not taking out or adding any moles of acid, you just squirting it out by adding more water.

X. It will not change. The acid is still the same in there (flask).

Y. The number of moles of acid will be the same, though ... because you're not adding any HCl and the concentration will decrease but if you do that then you have to take that into account in your calculation. Because you just changed the volume, then to find the moles it's concentration times volume and if you don't know the volume then you can't find the concentration.

Z. It's still the same amount of acid (because) it's just the same moles (you're) just diluting. It (water) doesn't affect it.

AA. No, because you only added 25 mls (acid) right, and the concentration is unknown ... I am stuck.

BB. It will decrease because the water will dilute it and make the concentration less.

CC. No, it does not decrease because you still not adding more moles of acid through the water.

DD. It will remain the same because as we add the water to the acid the volume is increased and the other way, the concentration is decreased. So from the equation, moles = MV, I think it's the same.
It will still be the same because you are not changing mole concentration; What you're doing is adding more water to it. So there'll be the same amount of moles.

It should be the same number of moles because in the beginning we had the same number of moles. It's just concentration that changes.

... It will not affect the number of moles because I added such in here. I suppose the molarity of this acid is 0.5 M. And that has 0.5 moles per energy litre. Then I take out 10 ml from here, therefore 10 ml that has 0.005 mole. If I add 90 ml of H2O in the 10 ml of the solution (acid) right, it will come to 0.005 moles per litre, right? Therefore concentration is changed but the number of moles don't change.

No, it will not; the water will not change the number of moles. It will only change the volume. The number of moles of HCl stays the same... the water does not have HCl.

... the number of moles will not change ... when you say moles you say how many atoms inside the solution do you have and so in this solution you will have the same as if it was without distilled water ... If you have 10 moles of HCl in a jar and I added 10 ml of that (water) ... there will be 10 moles per 10 ml and you can figure out the molarity by dividing such. But in this case when you have 10 moles per 60 ml which when you work out you get lower concentration but same moles.

... the number of moles is fixed because you're just adding water which is pure, it's neutral.

No it won't because you are not taking away any moles of HCl and you are not adding any.

The moles will be the same. Well, I mean if I added 1 mole of HCl, there's only gonna be 1 mole of HCl no matter how much water I add. You are not creating anything in there. The moles is not changed by the water.

No, it will still be the same because you are not adding more acid.

No, because you are not taking away or adding acid, it's just water.

You still have the same number of moles because your number of moles is there, you are just adding water to it.

The number of moles stays constant because you are not taking any out or you are not adding any.
QQ No, there will be no change there because ... it will be the volume that will become greater. Water does not affect it ... it doesn't take change the moles

RR Should decrease because when you add water it should compensate for the ... I am not too sure about that

SS Oh no, it won't affect the moles; you are going to have the same amount of moles in there but the concentration will change when the volume increase

TT The number of moles of acid stays the same because you are not taking out any acid and you're not putting in any

UU No it will be the same (but) I can't explain
Question:
11. How will the pH be affected by the added water?

Responses:
A The pH will drop; because H₂O is neutral it's going to lower it finally to neutral point
B The concentration will decrease so I think the pH too
C The pH will go down (since) the concentration will decrease
E It will stay the same. Water does not add any H⁺ or OH⁻
F Nothing, the pH doesn't change. It's (water is) neutral
G Basically the same because it is distilled water ... it's neutral pH
H The pH would change (increase) because pH is affected by the concentration
I It shouldn't affect the pH; water is neutral
J No, it will stay the same, water adds nothing
K I don't think it should. Water doesn't affect the pH
L We did that in class so I guess if you add water it wouldn't make any difference. Water is water
M The concentration will change so I think the pH will change but not much. Just a little higher
N It will change, with concentration, I think low may be. I'm not sure
O I don't think anything will happen to the pH. It's neutral
P No it won't affect it. Water is neutral
Q I am not sure how it will affect it
R It might be affected, that is, decrease if concentration is affected
S The pH may be affected but I'm not sure how
T The pH will actually drop again when you add water to it because the OH⁻ from the water will react with the H⁺ of the acid and so there will be less H⁺ ions
U It will not affect it. There's no excess $H^+$ ions added

V The concentration will decrease so it will affect the pH the same ... Lower

W The pH will be lower since the concentration will be lower

X The pH will probably decrease. May be (because) the solution will be dilute

Y Will be the same. I did problems before like that. When you add more water it doesn't affect the pH. Water is neutral

Z Water is basic, it might increase the pH

AA I don't think so that it will affect it, because water is neutral

BB It won't change because pH remains constant. If you add distilled $H_2O$ I think distilled water is neutral

CC It doesn't decrease. Yeah, that's the pH, that's it. The concentration decrease but pH doesn't. That's what I was talking about. (It doesn't decrease because) the hydronium ion is still there; you not adding any more and it's just water, it does give up some $H^+$ ions but it's not significant

DD The pH of the acid will be increased because the concentration decreased so (when we take the negative log of the concentration of the acid we find out the pH of the acid will be higher

EE Well, it will affect the concentration so it will probably affect the pH too ... It will make the pH smaller because the concentration will be less. It will be less concentrated so pH will be less

FF The pH never changes because in the beginning I had that much pH (pointing to acid in beaker) so we know the constant of the acid and we know the pH and we know the molar concentration of NaOH so what we trying to find is the concentration of the acid; so if the pH changes it's gonna be hard to find what the recent one is. So it doesn't change

GG It would not change the pH of acid if I add water. I know it would not change it. I read from the book, but I don't know why

HH Well, this (water) is neutral so, it would not affect it.
II No, I don't think so (but I am not sure. But if it did affect then there will also be a reaction inside here (beaker) an unnecessary reaction and that will defeat the purpose of the (HCl and NaOH) reaction

JJ Yes, if you add water, pH .... no, it won't affect it (pH). Water is constant, the concentration of water is constant - it doesn't change

KK No, O.K. I will change that, yes because it's less concentrated and therefore the ... I really don't know

LL Well, it won't (affect the pH) because both of these (acid and base) are strong acid and strong base. Neither of them hydrolyse, though. It won't really affect them. It will just be more H⁺ ions all over, but there'll be equal amount of OH⁻ ions from the water

MM As the concentration goes down, the pH will go up because it's the negative log of the concentration and if the concentration is going down because it's becoming more dilute, then the pH will be higher

NN I always get confused. It will bring the pH up towards the 14 end because you're decreasing the concentration of H⁺ ions and that is the pH

OO I don't think so because if the acid has a pH of 1, again it's set; you can add water to the acid and you still gonna have an acid with pH of 1. You just gonna be adding water which will be diluting the solution

PP It shouldn't affect it. No, it doesn't affect it because pH is given to you. Oh, wait a second, it does affect it because pH is sort of like a way of expressing H⁺ ion concentration ... As I said concentration is moles per litre. As you add water ... the concentration will decrease and the pH will go down

QQ It will increase the pH because the pH is negative log of concentration and as concentration becomes smaller its log will become more on the negative side and the opposite of the negative will be much larger

RR I guess it makes the pH rise because the concentration of the acid will be changed when you add water and therefore have different pH value. pH is derived from concentration so when the concentration changes pH should change, it should go up

SS Yeah, it will affect the pH of the acid; it will be lower, I am not sure (because) say the pH was greater than 10, that is before you added the water. If you add the water the pH of water is around 7 so I guess it will lower the pH ... If before you add the water the pH was 2, then it will increase it
TT The pH will go up because you're adding more base to it ... no, there will be no effect because you are adding both OH$^-$ and H$^+$ at the same time

UU I don't think it will affect the pH because the concentration of OH$^-$ and H$^+$ in your water will remain the same
Question:

12 If you use acetic acid instead of HCl in the titration against NaOH what will be the pH at the stoichiometric point?

Responses:

A It will be the same as for HCl and NaOH, (i.e. 7 since 7 is neutral point)

B I think it will be the same, around 4 for the reaction

C The same, that is 7, the neutral point

D I know acetic acid is a lot weaker so you'll use more moles of it but I don't think it should change the pH. It will still be 7

E That will be 7 as well. The H$^+$ and OH$^-$ will be equal

F The same as for HCl and NaOH, it should be 7

G Acetic acid is a pretty weak acid so it will be 5 or 6; less than 7

H It will be about 3.5 and 4. Acetic acid is not strong as HCl

I It should be 7. 7 is neutral

J 7 as well ... It's just that 7 is neutral

K The ratio will be 2:1 chemically speaking. I think it will still be 7

L It's still 7 but I know it's not right because this (acetic acid) is a weak acid

M It will be greater than 7 (as) acetic acid is weaker than HCl

N Somewhere between 8 and 10 because acetic acid is a weak acid

O I don't know that

P It will be 7 too at the endpoint because they will neutralize each other

Q Acetic acid is a weak acid so it doesn't have much H$^+$ ions in the beginning therefore you don't need that much base to put in. The pH will be 7 when there are equal amounts of base and acid
I don't know, may be it will be less

It will be 7, that's the neutral point.

Acetic acid is weak. I guess it will be at 7 too because it will be neutral.

It will be the same, 7, because you're still forming water.

It should be 7 because the $H^+$ ion concentration and $OH^-$ ion concentration should be equal and they are equal at pH of 7.

It's going to be basic because as you add the NaOH it's gonna combine with $H^+$ ions and make water and when you reach the equivalence point there's going to be these (acetate) ions which are going to shift the water equilibrium (thus producing excess $OH^-$ ions). There's going to be these (acetate) ions which will need some of these ($H^+$ from water dissociation) so that this $OH^-$ ion will go up and so it will be basic.

I will say it's still going to be 7 because that's when it's neutral.

Acetic acid is not a strong acid so it will go into equilibrium so it (the pH) will depend on the equilibrium ... I don't know (what the pH will be) probably 7, that's the endpoint.

You have a basic solution, (so) it will be higher than 7. Because it's a weak acid and a strong base, so you get a basic solution.

It should be basic so it will be between 7 and 14, on the basic side because if you have a strong base reacting with weak acid you get a basic salt and water.

7 (because) it's neutral.

It will be more basic, (pH of) 8, 9, 10 because you have stronger base and weaker acid.

The result will be the same. The pH will be 7 because it is the same as when we used NaOH and HCl; the only difference is HCl is strong acid and acetic acid is weak acid and so the difference is we only have to use less NaOH to titrate the acetic acid.

It should be just a little below 7 (because) well, NaOH doesn't really affect the pH. Acetic acid is stronger so it will probably become more acidic than basic.
The pH will be the same, one ... The pH should be the same no matter what acid you have in there (beaker)

Above 7 because we know acetic acid is a weak acid but NaOH is a strong base

pH will be zero, no if it reacts completely then it's neutral, and neutral has pH of 7

It will be the same, zero, very low (because) it's just water which is zero

Seven (because) it's seven where it changes colours ... because H⁺ ions from the acetic acid will neutralize the OH⁻ ions from NaOH so the pH should be 7

The pH will be below 7. Same reason as before (i.e. the ratio of the concentration of your base to your acid times Kb value will give you that)

Acetic acid is a weak acid so with a strong base it will be higher. It will be say 8, somewhere there

We're talking about weak acid and strong base. I think if this base is still strong it will still be able to take the hydrogen ions away from acetic acid and so it will still be 7 at equal moles as long as this (NaOH) is strong. But if this (base) were to be NH₃ or something, then it will be different

pH will be 8.7 because the acetic acid is a weak acid. At eh point when all of hydrogen is neutralized by the OH, you have still acetate ions left and because it's a relatively stronger base than chloride, it will hydrolyze forming hydroxide and more acetic acid and give you a higher pH

It will be probably above 7 because you have a strong base reacting with a weak acid

It will be higher than pH 7 because acetic acid is a weak acid ...

Well if the concentration are the same either the hydrogen will be taken out there may be a lot of acetate ions in the solution so it will try to attach itself, try to get some of the hydrogen so the pH will be a little more to the acid side. It will be higher than 7 because there will be more OH⁻ ions in solution

Higher than 3, I guess above 7 because acetic acid is a weak acid so NaOH will predominate and I guess .. I am not sure
SS It will be 7, because when the endpoint is reached there will be equal amounts of both in the solution and the solution will be neutral in order for the indicator to change colour.

TT 7 because they react one to one and then they will be neutral at 7, pH 7 is neutral.

UU It will be around 8.7 because ... well, I think there will be a buffer effect on the solution and therefore it will reach its pH as fast as ... and also near the stoichiometric point, the acetic acid hydrolysis too.
**pH**

**Question:**

13. If NH₃ is reacted with HCl in the titration, what will be the pH at the stoichiometric point?

**Responses:**

A  It will be 7 ... the same ... 7 is neutral
B  I think it's also going to be around 4
C  Should be 7
D  The same (pH of 7), it's still going to be neutral
E  It will be 7 as well. The solution at stoichiometric point is neutral
F  pH of 7, I am not sure. I think it should be
G  Ammonia is a weak base, may be a little more than 7
H  It will be about 8.0 to 9
I  It should be 7
J  7 at endpoint
K  No idea
L  I don't know
M  Since NH₃ is I think weak, I think the pH will be less (than 7)
N  I am not sure, but it may be lower
O  I don't know
P  7, that's the neutral point
Q  7 I think
R  It will be neutral, that's 7
S  I am not sure
T  7 (because) it will neutralize the acid
U  It should be the same 7 because you're forming water
V  It will be when it's neutralized and that's 7
W It's going to be acidic because the NH₄⁺ ions will combine with OH⁻ from water to form excess H⁺ in solution so it will be more acidic

X I think it's still going to be 7

Y Probably 7 (because) that's the endpoint of the reaction, when the H⁺ ions react with hydroxyl ions

Z That will be acidic, (because) NH₃ is a weaker base so it will be less than 7

AA Ammonia is NH₃. It will be basic because NH₃ is a weak acid ... It will be acidic because if you have a weak (base) reacting with a strong (acid) you always get the characteristic of the strong acid in the salt

BB Below 7 because they are both acids

CC I think probably, roughly around 7. I know HCl is more strong acid but I'm not sure of NH₃. I guess ... actually I will have to change. I suppose it will be fairly neutral or probably more acidic. We haven't used NH₃ that much so I don't think that this (neutral) is the case

DD It should be the same (pH of 7) because everytime you titrate two solutions they form a base (student meant salt) and water which is neutral. I mean the pH is 7; so long as we titrate an acid and a base you have pH of 7

EE I think it will be towards the basic ...

FF It will be, again, still the same, pH less than 13, one

GG I think it may be pH 7 because though you use ammonium hydroxide instead of sodium hydroxide, may be you have to add from here (student points to the volume of the base at the start of the titration) to here (student points to the volume at which reaction will be complete - this was a smaller volume). If they will react completely, then I think it will be 7

HH The endpoint is neutral so pH is 7

II I am not sure about NH₃, but I believe NH₃ tends to dissociate. HCl tends to dissociate completely (but) I am not quite sure about NH₃ ... I am not sure

JJ 7; the same reason (that is, 7 is where H⁺ ions neutralize OH⁻ ions)

KK I don't know
... pH will be lower than 7 because you have a strong acid and a weak base.

It will still be 7 as long as it is a strong acid.

The endpoint is below 7 pH because I'll say the hydrogen from HCl will react with all the NH₃ at the endpoint to give NH₄⁺. It will hydrolyze and go back to give NH₃ and H⁺ ions.

Strong acid will take over and neutralize NH₃ faster and the H⁺ concentration will be greater and when you convert that (greater H⁺ concentration) to pH, it will be a smaller pH, less than 7.

NH₃ reacts with water to produce hydroxide and ammonium ion. NH₃ is a weak base. I am not sure. We didn't do weak base - weak acid titrations but I'll assume that it will be neutral because when you use strong base strong acid it becomes neutral.

It will be lower than 7 because NH₃ when it reacts with hydrogen becomes an acid and therefore there will be more acid in solution.

I guess around 3 because HCl is a strong acid ... I am not sure of NH₃.

I am not familiar with that at all.

O.K. ammonia is a weaker base and HCl is a strong acid. O.K. now pH should be lower to maybe 5 or so.

Between 0.1 and 6 (because) ... In the case of acetic acid it's a weak acid and I think ammonia is quite a bit stronger acid so I think the pH will be lowered a bit near the endpoint. (Student indicated previously that NH₃ cannot react with HCl).
Indicator Behaviour

Question:

14. Why is an indicator needed in this titration?

Responses:

A  It's a way of showing the reaction is neutral otherwise you'll be too far out

B  To try and find out what the pH of the solution is

C  To determine when the solution is neutral or has reached pH of 7

D  You got to have a colour change to show it's neutral, otherwise you won't be able to tell

E  To indicate when the same amount of OH⁻ and H⁺ have reacted

F  It tells you what the concentration or pH of the acid and base is in the final solution

G  To get the endpoint when the pH is 7

H  Well, after neutrality is made and when it goes on just a tiny bit beyond neutrality then the indicator shows up

I  To show the colour if it's turning into neutral or acid. First it's acid and the indicator will tell when it's neutral

J  To show you ... indicate when the acid and base neutralize

K  The number of moles affect the phenolphthalein and the phenolphthalein also changes colour. Normally it will reach equal balance and you won't know it has reached equal balance. The indicator tells us because the indicator itself changes colour at that point

L  To note colour change when titration is complete with OH⁻ and H⁺ in solution equal

M  So you can tell the equivalence point. You can tell when all the acid is used up

N  It's to tell you when it's hit the endpoint where they are sort of even; that is, when the number of moles of acid is equal to number of moles of base

O  No, not really, I don't know
Because, that way you can notice the change when the right amount is in there ... when the right amount of acid and base is in there you notice the change so you get the volume of base.

It indicates when or at what point the moles of base equals moles of HCl.

Oh, because if you don't have an indicator you wouldn't be able to tell whether you've put enough of each one (acid and base) in there ... whether it's neutral.

So that when all the HCl react with NaOH that's at that point the pH will determine if the solution has the same colour as that (colour of distilled water containing drops of methyl orange). This is the only way I know That's what I learn so far.

In determining the concentration of the hydrogen ion.

To show when the solution becomes basic.

So you know when you've neutralized the acid or base because once it becomes basic I know they already neutralize and there's already too much base in the solution.

To know when a solution reached a certain pH because it will show you the range of pH of the solution.

To check to see if the pH is where it should be. It should change between 6 to 7.6.

It indicates when the reaction is complete ... when reaction of $H^+$ and $OH^-$ is complete - no excess $H^+$ ions.

It's supposed to change colour when it reached the end-point and the solution is neutral.

It indicates when there's enough acid reacting with base.

It tells you whether the equation (solution) is basic or acidic.

Just indicate when the endpoint is reached and it should be chosen to be close to the stoichiometric point .. when the concentration of the $H^+$ is equal to $OH^-$.

To show when equilibrium is established, ... the reaction is finished ... when $H^+$ and $OH^-$ are equal.

It indicates when the solution is neutral or within the stoichiometric point.
Phenolphthalein changes to show there's enough amount of acid in there ... to get equal amount (of base) to react with HCl - when they get the same, ... same concentration of acid and base

... If 1 mole reacts with 1 mole; if there's more base in the solution it will turn pink. So it tells when there's more base

To show when HCl and NaOH have reacted completely - when there's no more HCl

To tell when the endpoint is reached (that is) when certain molarity of HCl reacts with certain molarity of NaOH

You can tell when the amount of $H^+$ ions and $OH^-$ ions are equal, like the endpoint

I don't know exactly how it works but it's to show up ... I mean, it helps to see when you've reached the equivalence point

Otherwise, I won't be able to tell exactly where the concentration was. In the beginning, phenolphthalein tells me that the pH of this substance down here (acid) is roughly that zone (pH8-10), whereas when it goes pink, it means I went past the zone. But it gives me more, in other words, I wouldn't have a clue where I was

So you could tell when the amount (of base and acid) has been equalized...

I am using indicator to tell us when we reach the point when the acid has neutralized the base. We could use a pH meter but these (indicators) are O.K.

So I can find the point when the number of moles of hydroxide ions is equal to the number of moles of acid. It's the point when NaOH has totally used up the acid and you should have equal number of moles of acid and base

Because when you add acid to base you can't tell when you have equal number of moles of each solution ... the pH of the base right now is 13. We want to lower it to 7 where we have equal number of moles of acid and base reacting with each other. Therefore you have to have an indicator to indicate when you have reached that endpoint ... that's the stoichiometric point

Because you can't be certain where the endpoint is, you need something that will tell you when you reach the endpoint ... when the moles are the same
RR So that when you have reached the endpoint, the colour changes

SS To tell you, you have reached the endpoint ... equal amount of acid and base

TT Because the NaOH and the HCl will not change colour; you need an indicator to tell the point where it changes, they are equal

UU To know that you have reached the endpoint or stoichiometric point
Question:

15. You noted that the indicator had different colours in different medium, how does the indicator change colour?

Responses:

A I guess there must be some sort of a breakdown in the bromothynol blue

B I have no idea, just like magic

C It's the effect light has on electrons in the solution

D No I don't but I guess it would react with the H⁺ in the solution to change the colour

E The indicator is just a molecule and there's two forms - one form has a H⁺ ion added and one form hasn't. The 2 forms aren't the same colour so if you have more H⁺ may be the equilibrium shifts to the side that has the mole rule with H⁺ ion so that in this case (phenolphthalein) that one will be pink

F I don't know

G I am not sure but I know it's something to do with the transfer of electrons

H At certain H⁺ concentration the indicator reacts with the base or the acid and that forms certain things which have different colours

I I don't know

J I know when there's H⁺ ions, indicator is clear and when there's OH⁻ the indicator is pink. But I cannot explain how it happens

K Well, because they (indicators) just absorb the OH⁻ ions to form complexes. That's why initially when you add the drops (of NaOH) it (the solution) turns purple right away. You have to swirl it around so that it mixes with the HCl as well. Then you have to add more until there's enough for the HCl and the HCl has reached the same amount of OH⁻ that it needs and there's no more to be absorbed by HCl anymore and so phenolphthalein itself can hold on to it and it changes colour

L Because there was enough base so the pH changed and made visible the indicator, I think I am not sure how
The indicator is an acid and the undissociated indicator has one colour and has another colour when its broken into its ions. So when enough base is added it starts reacting with this thing so you get $X^-$ which give colour change (that is if $HX$ is the colourless form of indicator)

Phenolphthalein is an acid but when you add base the equilibrium shifts so that its conguate base or acid or whatever is formed. If phenolphthalein in $HA$ then when you add the base as in this equation $HA + B^- \rightarrow HB + A^-$ the equilibrium shifts to the right and you have $A^-$ from the indicator

I don't know how it works

No, I don't

I don't know how it changes; I know it's yellow in acid and blue when moles of $OH^-$ is more than $H^+$ ions

I suppose when the acid is more than the base then it changes colour. But I don't know how it changes colour

The indicator is a base or an acid. O.K. if this ($HB$) is red and this ($B^-$) is yellow right. Like here: $HB \rightarrow H^+ + B^-$ If there's more of this ($B^-$) which is yellow then this ($B^-$) will dominate

Well, I'm not really too familiar with that but from what I heard an indicator is a weak acid and the way it combines with the solution at equilibrium determines its colour or its actual concentration

Once you reach pH 7 it's neutral and both acid ions and basic ions are equal and the next drop of $NaOH$ makes it basic and that amount of basic ion reacts with the phenolphthalein to make it pink

I don't know. It might be because of its reaction with the $OH$ ion that causes it to change colour

I think it's a weak acid but it shifts its equilibrium when you add $H$ or when you add $OH$. One of the reactants is one colour and one of the products is another colour so if I shift it toward the pink by adding $NaOH$ then it would look pink

It changes colour when the concentration of the $OH^-$ has reached the same concentration of the hydrogen. The concentration is around 6 to 7.6

The indicator can lose protons which react with the base forming water. Therefore the ion is pink in colour but phenolphthalein as colourless is not an ion. ... (Indicator) in an acid salt solution that changes colour when it losses protons
Z I don't know

AA I don't know

BB No, oh, this is basic ... I don't know how to explain it

CC It gives off a negative ion and that's the colour of the negative ion. When it combines with the hydroxides and then forms water and gives off negative ions, the negative ion gives the colour. (The indicator) is a weak acid

DD May be there's some reaction between the solution and indicator and the indicator has some ions which are coloured ... When they (HCl and NaOH) have reacted, the substance turn out to be free ions and so it changes the colour, I think ... I don't know (what substance an indicator is)

EE I am not sure ... I don't know

FF This (phenolphthalein) is acidic and it goes towards a base now. It's in equilibrium

GG ... It combines with the OH⁻ to form something and therefore it changes colour. I don't know the formula of this acid (Phenolphthalein), therefore I only assume it combines with OH⁻ to fore coloured substance

HH ... When it's losing H⁺ ion, proton, then the structure is different, therefore it takes on a different property and change colour

II I am not too certain on indicators. I just realize it does change colour. I am not too quite clear on that. I don't know

JJ The HCl gives off H⁺ ions to this indicator. This (indicator) is a really weak acid; it (HCl) gives off H⁺ ions to the weak acid so during titration, the H⁺ ions (from HCl) get less so then as the H⁺ ions get less the equilibrium - of bromothymol blue - goes back the other way. Like it's yellow right and purple in base and that's (yellow) in acid, as yellow purple (H⁺). If you had H⁺ ions this (right) side, it changes to yellow. When there's no H⁺ ions the equilibrium goes back this way (to the left) so it will be purple

KK I don't know

LL Phenolphthalein is a substance. When hydrogen starts getting taken off the indicator, it's ions have a colour ... the indicator ion is say pink. But when the pH of the substance goes up it (indicator) starts donating hydrogen
MM I am not sure

NN By the gain or loss of $H^+$ ions by the indicator. If the indicator was acid it will change colour by losing a proton and if it has already lost the proton, it can change by gaining it back. It (bromothymol blue) has equal amounts of acid and base which they call conjugate in equilibrium and the pH 7 is when there's equal amounts equilibrium and one of them, the base, I think, is yellow.

OO Like this is the equilibrium right now (student writes the following equilibrium for the 2 forms of the indicator: $HP_i + H_2O \rightleftharpoons H_3O^+ + P_i^-$) ... As the hydronium ion from this (equation) starts getting consumed, there'll be a stress on the right so it (the equilibrium) will shift to the ... right so it will start producing more of it's salt ($P_i^-$) and therefore that will change the equili­brium ... and a different ion is produced which is pink.

PP I never was taught. I think I was told but I forget. An indicator is usually a basic or an acidic type of solution. Bromothymol blue is basically a neutral indicator, I guess, in that at at pH 7 when the $H^+$ concentration is equal to $OH^-$ concentration it changes colour ... I don't know actually.

QQ It reacts with the acid and it tries to trade off the conjugate bases but the acid with a stronger conjugate base is the one that show up. Like right now, this acid, phenolphthalein, its base is weaker so it will be ... what I mean is it trade off and it changes colour because the phenolphthalein which used to be an acid ... now it's in the base and its hydrogen is weaker than the conjugate base instead of ... somewhere else. It's forced to that because otherwise it's not stronger ... I always get that confused.

RR There is a chemical reaction that take place. I do not know what exactly but a reaction takes place.

SS When it reaches the pH of 7, when ... I don't know.

TT Because this (phenolphthalein) is a weak acid and it's a weak acid because it changes in this range (pH 8-10). This acid changes its colour when you add so much NaOH ... I don't know how it goes about changing its colour.

UU I am not quite sure. The teacher said an indicator is like a colour molecule so I presume it donate hydrogen. I don't know.
Question:

16. Do you think the amount of indicator added will affect the final volume of base used in the titration? Why?

Responses:

A  I don't think so, I am not sure why but it might make a darker colour or a more deeper colour but it wouldn't affect the reaction, that I know

B  I tried that in class and I think it makes a better more visible solution but it doesn't affect the volume of the base

C  Yes, well no, if you add too little then the colour change wouldn't be as perceptible

D  No, if you add more it's easier to tell because the colour change is more clear

E  No, it will just make the colour change right away

F  No. It's just an indicator. You need it to show colour change

G  No, I don't think so. It will only be deeper

H  There's no effect. The indicator shouldn't really affect unless you've got a lot - a couple of millilitres of it then it would react with the acid

I  No, if anything it's the colour which will be deep

J  Yes, I think if you add a drop the colour won't show so you have to add more and more base but if you add more indicator then the colour will show early

K  To some extent ... it will absorb extra OH⁻ ions because that's the principle with which this works. So if you have too much of this (indicator) and this absorbs too much of the OH⁻ then your recording will be slightly off

L  Not really. I wouldn't think it makes a lot of difference. It only gives a colour change. But I think if you used a certain number of drops you should stick to it, I guess

M  It will give you a more definite colour but this is not enough reason because it is an acid itself and it will start to change the pH and your results

N  If you add a lot more it will slightly affect the volume because you've got an extra volume in there ... which will make the final volume of base more than 25.4
O I don't think it will, it's only an indicator ... It shows only the (colour) change

P I don't think there's an effect. The indicator is just to bring out the endpoint so you could notice the change. If you don't have the indicator you wouldn't notice the change

Q No, it won't because you're calculating the volume of base from there (volume in the burette) which you put in not the volume that's in there (flask). So you know the exact amount of base and acid in there even though you have a large amount of indicator. That's just for preference whether you want the colour to be really deep or light

R I don't know, but if you use more it's easier to see the colour change

S It may have an effect (but) I don't know

T I don't think so. It only makes the colour darker

U Yes, I think it might because then there will be greater amount of phenolphthalein dispersed and that will make it more sensitive so that there's more phenolphthalein to react with the base

V I am not sure. It might but I don't know

W No, because even if there's more phenolphthalein the equilibrium will still be the ratio between the reactants and the products. It's gonna be the same. There's more of both the reactants and the products and more of the indicator but the ratio between the reactants and products is the same and so when the equilibrium is shifted the ratio will be the same and so the colour will be the same

X No, it's just an indicator. It's concentration has no effect. It does not contain any hydrogen or hydroxyl ion so it wouldn't change the concentration

Y No, because it doesn't have any $H^+$ ions to neutralize either the acid or base. It's just a neutral substance. It just indicate the colour, that's it. It doesn't interfere with the reaction of the hydronium ion and the base, the hydroxyl ion

Z If you add a whole lot, it won't change because it's just the same endpoint. It (indicator) only shows the endpoint

AA No, it shouldn't because if excess of this (phenolphthalein) is used it only indicates the equilibrium endpoint
BB It doesn't really matter because you get the volume here (student points to the burette and the volume of acid in the flask). It (only) shows the endpoint.

CC No, it doesn't make any difference (because) it's a weak acid and it's so weak that it doesn't have any hydronium ions to really make a difference when titrating or have any OH⁻ ions. It just makes it (the colour) more visible...

DD I think if we add more it doesn't affect the results because if we want the resultant solution to reach a pH value of 8-10 and we have to use a certain amount of NaOH this (phenolphthalein) is only an indicator so I don't think it would affect the results.

EE Might have a bit because it is an acid; indicators are an acid so might affect it but not too noticeably ... so long as you don't use more than say 2% of your volume of acid.

FF It will affect the result (Student looks at pH range of indicator). The more drops of the phenolphthalein there's the larger the pH of the solution so we need less base, we need lesser base.

GG Yeah, it will affect it (because) I know it will affect it but I don't know why.

HH I don't think so because it doesn't matter how much you add, this (indicator) is still a weak acid; it will not react until the HCl has reacted completely. So it wouldn't matter.

II It never occurred to me. We are just told to use it ... No, I really don't have any answer to that.

JJ Yeah, it's acid, right, so it gives off H⁺ ions to make it more acidic. The volume of NaOH will be different, may be increase.

KK Yeah, it would affect it because if you had too much (indicator) in there, then when you added your base, it would probably change right away, a lot quicker (because) well, it's just a lot easier to see the colour change with few drops.

LL No, it wouldn't have any effect on it because phenolphthalein itself is basically a bystander and its concentration or amount you put in doesn't affect the titration results. Probably the colour will be more intense.

MM No, but will make colour change easier. But it won't affect the amount of base used because it's just sort of standing by; it's not involved. It just indicates.
NN  I have a feeling it wouldn't matter. It wouldn't affect the concentration of the acid in the thing (flask) because you know what it was to begin with ... I have thought about that, I think it would affect it. In its state it (bromothymol blue) has a pH of 6-7, I think. (It will affect it) because it's blue and it neutralized some of the acid in changing it to yellow when you mix it with the acid. So that will take out some of the H⁺ ions that will be normally used to neutralize NaOH

OO  No, I don't think so because it still gonna be a weak acid right in there and it's only gonna react once all the H⁺ has reacted and it gets into the pH range where the OH⁻ ions start to react with H⁺ ions from the indicator

PP  It shouldn't affect it because I guess this (indicator) is somehow like water except it changes colour ... So if you've got 0.1 moles of acid in there (flask) you just want to find out how many moles of base you add so I guess it doesn't matter what the concentration (of the indicator) is down here (in flask) ...

QQ  No change, phenolphthalein is an indicator; indicators doesn't actively become involved in the reaction ... It reacts like a catalyst

RR  No, it only tells the endpoint... It shouldn't affect the outcome of the experiment. I don't know why. It's just that it shouldn't affect it

SS  No, because it doesn't matter how many drops you have of the indicator because ... It doesn't matter how much you add, does it matter? I don't think it matters because I did it before. I did it once with a couple of drops then I made a mistake with something and used too many drops, probably half the bottle, right?... and then there was no change

TT  Yes, because this (phenolphthalein) is a weak acid and if you have more acid then you have more acid there (in the titrating flask) to neutralize so it will affect the volume of the base

UU  I think it will have an effect because the indicator, I think is a bit acidic and it will affect all the stoichiometric points. The stoichiometric point will not be where it is with the 5 ml of the indicator. It could be probably more, ... it will take more base
Question:
17. Why did you choose this particular indicator for the titration?

Responses:
A. Well, that's just because that (bromothymol blue) is the only one I've ever used. I've seen the different colours of phenolphthalein and methyl orange but bromothymol blue is the only one I ever used.
B. Because that's (phenolphthalein) the one we use in class.
C. Because the colour change (for bromothymol blue) is green at the neutral point whereas the other ones (phenolphthalein) have colours at this point which are intermediate and not so distinct. I am not so sure about methyl orange though.
D. I think I have heard of it (phenolphthalein) more like whenever I am doing titration. I have heard of the others but I have never used them.
E. Because phenolphthalein changes in colour from clear to pink and this is approximately the same point that number of moles of acid equal the number of moles of base. The stoichiometric point will be around 7 but (this) is not really important because if you drew a graph of pH against volume of base added you come up with a sharp change so both points will be almost on the same straight line.
F. I would think that the pH range of phenolphthalein is appropriate, just a little basic.
G. I chose all indicators just in case one of them didn't indicate the endpoint.
H. Because it (phenolphthalein) would indicate about the point when the pH level of HCl and NaOH at the neutral point is past 7 which is the neutral pH. It also gives a distinct sharp colour instead of the gradual colour change of bromothymol blue.
I. Because it (bromothymol blue) has a pH which change from 6.0 to 7.6. The solution in the flask will be neutral at 7 and 7 is in the range of change 6 to 7.6 so it will tell when neutral.
J. Because it (phenolphthalein) is colourless in acid until pH reaches 8.
K Well because the range phenolphthalein changes colour is between 8 and 10 and that's the pH the reaction ends and at which the concentration will be equal; that's when the colour changes. Hold it, pH of NaOH is 13 and that of HCl is 1. It's all from experience, that's what I used the last time

L Because you can see a definite colour change (with phenolphthalein) and I think that's the one we used in class

M It's (phenolphthalein) got the right pH range approximately for the reaction of strong acid and strong base which is 7 but the graph shoots up straight (and) the pH of 7 and 8 are essentially the same place

N I don't exactly know why, I know it (phenolphthalein) starts to change between 8 to 10 in the acid. It will change when it starts to go to base which is somewhere around 8 or 9 then it will turn pink

O I don't know. I just know I have to use one of them so I used this (phenolphthalein)

P Now I remember (should use methyl orange because methyl orange is for acid (that is when acid is in the flask) but those (phenolphthalein and bromothymol blue) are higher (in pH) so they are for base (that is when base is put in the flask)

Q I think the methyl orange changes to neutral at orange and it's kind of hard to tell the difference between red and orange. Bromothymol blue changes to green when neutral so it's more distinct

R I used bromothymol blue because I never used any of the other ones

S Because this one (methyl orange) is easier to see, I guess that's why I used methyl orange

T It (bromothymol blue) had a range that is adequate - really between the neutralizing area. Like, to find the appropriate colour you can go to one of the extremes (pH6 or pH 7.6) and kind of get a close approximate more or less because 6 is closer to 7; 7.6 is too

U Because that's what I know. Plus it (phenolphthalein, pH 8.2 - 10.0) looks for base and since I am having base (in the flask) it should work out that once I have one drop too many base and it becomes basic it should change colour. But if I have the base in here (flask) then I can use methyl orange
Because this (solution in the flask) is acidic and this (phenolphthalein) changes colour in the basic range so once it's neutralized there will be too much $OH^-$ ions so it becomes basic and change colour.

We used it before in the lab for doing acetic acid and titrating it with NaOH and so I knew that it would work. Also phenolphthalein changes at 8.2 which is just slightly past neutral.

Now from what I know, the pH of this (base) is 7 and this (bromothymol blue) should change prior to 7. It should change when the pH of the acid has reached between 6 and 7.6.

Because we used this (phenolphthalein) in the lab.

I don't know.

Because we used it in the lab ... (also used phenolphthalein because I thought concentration might be in that range (pH 8 - 10).)

We did a lab and that (phenolphthalein) is what we used.

Well, the solution will almost be neutral for strong acid and strong base and that's why I chose bromothymol blue because it's closer ... the indicator pH must match with the stoichiometric point.

Because I did it in experiments in class. We used this (phenolphthalein), Maybe because the pH is 8 - 10 ... Maybe after the reaction the resulting solution may be basic.

Because it's (bromothymol blue's range) in the stoichiometric point.

Well in the beginning I have seen the result of phenolphthalein in the lab so I used it.

Because I always use this one (phenolphthalein). I don't know about these two (bromothymol blue and methyl orange).

Because it has a pH of 8, that means it's quite basic, it's not strong acid. Also the colour is quite clear so when it turns coloured, then I know but this (methyl orange) will colour it ... Because it's clear in acid, that's why I'm using it. I don't know really because I never used those (bromothymol blue and methyl orange). I have only used phenolphthalein.
II Well, this is what we generally use, I have to admit. I am not sure, of what pH level we've already done NaOH and HCl and we used phenolphthalein. We've never really explained about pH level (of indicators)

JJ Because it (bromothymol blue) is closer to zero, closer to 7; pH 7 is neutral

KK Because it (phenolphthalein) is in the right pH region. (Asked what he meant by that, student replied) That's what we used in class

LL Because ... at the pH when there are exactly the same amount of moles of $H^+$ and $OH^-$, the phenolphthalein will tell you when it's pink. I know it's phenolphthalein because we've used it in the titration for these two compounds before. I don't remember exactly why

MM Well, this (bromothymol blue) changes about 7 and this (phenolphthalein) changes about 8 to 10. Then if this (bromothymol blue) has changed already ... Well, I am not sure, though but I think I have to use phenolphthalein. We used it in the lab

NN ... It's a complete reaction, there'll be no hydrolyses of Na$^+$ and Cl$^-$ so I should use this one (bromothymol blue) because it's about pH 7 of water. Well, it changes colour at pH 7 when it (the solution) is neutral

OO Because it (phenolphthalein) seems like a good one to use. That's what we used in our lab work

PP Bromothymol blue, its pH is 6 to 7.6. When the NaOH reacts with HCl you going to produce water, sodium and chloride ions. The water has pH of 7 therefore when the pH gets to around 7 which is about the middle point (of the indicator), if it gets to pH 7 that means pH of the solution is 7 and equal moles of HCl and NaOH have been added together

QQ Because I wanted something that will come, that will be in the 7 range ... that is, when it is supposed to be at the endpoint which is when it's neutral, 7 is neutral

RR Because this is an equilibrium reaction and when it reaches the endpoint it (phenolphthalein) will turn colour which will tell me it's good. Also we did use this in experiment so I just want to use it

SS I don't know (why I chose phenolphthalein). That's the only one we use in class

TT Because ... this (NaOH and HCl) should react completely between pH 8 and 10
Because it (bromthymol blue) has a pH range of 6 to 7.6 and when I titrate it I want equal amounts ... and after the reaction the pH will be around 7, that's the stoichiometric point.
Question:

18. If acetic acid is used in the titration instead of HCl which of the 3 indicators (bromothymol blue, phenolphthalein and methyl orange) will you use in the titration?

Responses:

A Bromothymol blue because it's the only one I'm familiar with

B I will probably use the same indicator, phenolphthalein. This is what I use in class

C No, I don't know

D Phenolphthalein because I always use it in titration

E Phenolphthalein because stoichiometric point is still 7

F Phenolphthalein because of the range of the indicator which is basic

G Bromothymol blue because acetic acid is a weak acid. The pH of 5 or 6 is what I expect acetic acid to be

H I'll probably use the methyl orange ... because acetic acid is not a strong acid and equilibrium will be shifted toward the acid

I Bromothymol blue because the pH is around 7

J Bromothymol blue because acetic acid is a very weak acid so it will be easier to tell the colour change if the pH changes to 7

K I will go for the phenolphthalein, again from experience

L Methyl orange since it's a weak acid

M The pH at equivalence point will be 7 so phenolphthalein will be suitable

N Phenolphthalein just because it will give you a pH that's gonna be a bit higher than the neutralization point like the acid in that (flask) so then you know that you may be beyond it

O Bromothymol blue, I don't know

P If the same procedure is used (that is acid in flask) then I'll use the same indicator (methyl orange) because it's for acid
Q I'll probably use bromothymol blue because the pH (of final solution) will be around 6 to 7

R Methyl orange, ... I guessed

S I will use this (methyl orange) and this (bromothymol blue) together. First I will get the standard (by putting drops of each in test tubes containing water) and then do the titration using this (methyl orange) alone and then do another using this indicator (bromothymol blue) only ... (but) I don't know which one to choose

T Most likely it will be bromothymol blue because it's within the neutralizing range (of 7)

U If I was using the acid in the flask I will be using phenolphthalein otherwise I will use methyl orange

V The phenolphthalein because acetic acid is acid and you wanna know when it becomes basic and the other indicators are for acids ... So (if the base is in the flask and the acid in the burette) I'll use methyl orange

W I will say phenolphthalein because again that (phenolphthalein) is slightly basic, 8.2 the point that it changes and because I used it before in an experiment with acetic acid

X I will use methyl orange. O.K. put it this way; supposing I used the right indicator in the first (titration) then I will use one that is smaller, that's got a lower pH because ... No, I'm sorry, a higher pH because acetic acid is not going to be strong so it's pH is going to be actually close to 7. I will use one that's close to 7 probably that one (bromothymol blue). I definitely wouldn't use 2.9 (methyl orange) because that will be for strong acid like HCl. I probably should have used it (in the titration)

Y Phenolphthalein because acetic acid is a weak acid

Z Probably the phenolphthalein because it's (pH range is) between 8 and 10

AA I will use phenolphthalein because it has a range of pH on the basic side too (i.e. just like the pH of the final solution)

BB Phenolphthalein. I don't know (why)

CC Phenolphthalein because it's end point will be closer to the stoichiometric point pH (of 8 to 10)
I will use the same indicator (phenolphthalein) because the pH of the resultant solution is the same as the HCl + NaOH

I'll still use I guess methyl orange or bromothymol blue because the pH level is still near the stoichiometric point. Probably not too much methyl orange because it's still pretty too much acid because pH is still lower. I will use the bromothymol blue

Well, one thing, I haven't used these (bromothymol blue and methyl orange) so far. I will use still this one (phenolphthalein) because I'm more familiar with the colour

I can't use methyl orange because the pH is 3.4 - 4.6 so that's a weak acid but if the pH is above 4.6, I think there may be some change. But I haven't used this one (bromothymol blue) before so I will use phenolphthalein

I have to find something that's a weaker acid than acetic acid. This (methyl orange) is quite acid so I guess I will use this (phenolphthalein). It's the most basic. It has a pH of 8 to 10, that means it's quite a basic solution... If I have to choose an indicator I have to choose one that's a weaker acid than acetic acid

I am not sure what indicator (to use)

Bromothymol blue. I try to use one which is closer to 7

The phenolphthalein because we used it before

Phenolphthalein because it will be over 7.6, the pH of the solution

That's why I chose this one (bromothymol blue) originally because I thought it would be 7 but then when I put it in the acid it seems it's already gone for a colour change. But well, I still think this one (phenolphthalein) will be good (because) well, it had a colour change... I haven't used this (bromothymol blue) before

I'll use phenolphthalein because it covers the pH of about 8.7 for the (final) solution

Phenolphthalein because it's got a pH range from 8 to 10 that I assume is around that of the solution

I will use phenolphthalein because its pH changes above the 7 range... This (reaction between acetic acid and NaOH) I guess, its stoichiometric endpoint will be higher (than 7) therefore you need an indicator which has a high pH range
QQ I will use ... probably the same one I used (phenolphthalein) because since it (pH) will be higher; this one bromthymol blue) doesn't have enough range, like it's down to 7.6, it's low and the other one (methyl orange), is much too low

RR I guess this one (phenolphthalein) because the pH range is between 8 to 10 and since the pH was above 7, I will use this one (phenolphthalein)

SS The first thing you need is whether the acid is strong acid or weak acid. I know HCl is strong but acetic acid ... I don't know

TT I think I would use phenolphthalein because it changes between 8 and 10

UU In this case I will probably use phenolphthalein because the change in pH is around 8 something and phenolphthalein is the right indicator
Question:

19. If NH₃ is used in the titration which indicator out of the 3 will you choose?

Responses:

A  Bromothymol blue, just that I have used it before
B  Phenolphthalein, maybe ... I don't know
C  I don't know
D  Phenolphthalein, also because I use it in Lab
E  Phenolphthalein
F  Maybe phenolphthalein because of the range
G  Phenolphthalein because pH of NH₃ should be around 8
H  I'll probably use phenolphthalein because ammonia is a weak base
I  I will still use bromothymol blue
J  Phenolphthalein, it's easy to see the change
K  Phenolphthalein ... that's from experience
L  I guess I will use phenolphthalein because we use it in the lab
M  Phenolphthalein
N  Probably phenolphthalein ... I don't know why but maybe it's a bit higher than the neutralization point
O  Bromothymol blue ... I just think it will work
P  I think methyl orange if acid is in the flask
Q  Bromothymol blue because it's around the pH
R  I don't know, may be methyl orange again
S  I don't know
T  I will say bromothymol blue, again it's within the range
U  If acid is in the flask, I will use the same (phenolphthalein)
Phenolphthalein if you put the acid in the flask and you want a basic solution

Methyl orange because you're looking for acid solution

(Since) the pH is 7 for the base I'll still go for this (bromothymol blue)

... use phenolphthalein because it's a strong acid with a weak base. The weak base will dissociate 100 percent

Probably methyl orange (because) it's less than 7, this one (bromothymol blue) is less than 7 too

I guess methyl orange because it has a lower pH

Methyl orange because it is an acid indicator

Methyl orange because its endpoint is acidic on the pH scale and your solution is probably acidic so the endpoint and stoichiometric point coincide; that's how you choose your indicator

I just have to use the same indicator (phenolphthalein)

I think it will be towards the basic so I probably could use phenolphthalein

I'll probably use the same indicator (phenolphthalein)

I think I may use this one (phenolphthalein) too because I know this (phenolphthalein) much more than any of these

I will use phenolphthalein, again (because) phenolphthalein is weaker than HCl

I don't know

Same as that one for acetic acid (that is, bromothymol blue)

Same one (phenolphthalein)

I will like the bromothymol blue

I will still use the phenolphthalein

I am not sure ... maybe in this case it will be methyl orange

I will use that (methyl orange) because NH₃ will be a weaker base

Bromothymol blue
QQ I will then use the methyl orange
RR I will use this one (methyl orange)
SS I don't know. I am not familiar with the reaction
TT Methyl orange
UU Methyl orange
Question:
20. Do you think you could have used any of the other indicators in this titration? Why?

Responses:
A Methyl orange has a range 2.9 - 4.6, that would be basic 7 is neutral; I don't think so because bromothymol blue (which I chose) seems to go into acid and base, 6.0 - 7.6 so on both sides of the scale. Methyl orange seems to be below 7 and phenolphthalein seems to be above 7

B (No), because we never experimented with these (bromothymol blue, and methyl orange) in class

C I couldn't have used methyl orange but I don't know why. The colour is not distinct (with phenolphthalein)

D I could have used methyl orange or bromothymol blue they are all indicators, I have only have to know the colour change

E No, not methyl orange. That would have been a bit too far out. The endpoint won't be too close to the stoichiometric point. It would be far away. I think I could have used bromothymol blue because it's (pH is) on the same straight line

F No I couldn't have used methyl orange because the pH range is not high enough

G I am not sure but maybe phenolphthalein probably could have given a good indication, though pH is a bit high, but with methyl orange, no because the pH is lower.

H You could have but it won't work for this one because the pH (for methyl orange) is 2.9 to 4.6. It would have done (i.e. the reaction would have been complete) when the pH was 7 but before then it would have reacted immediately. (With bromothymol blue) even before pH (7) is obtained it would react .... even before neutrality is obtained because it starts at pH of 6. It would change before neutrality is reached

I No, I could have used (methyl orange) because this (acid solution in flask) is already acidic. That's (phenolphthalein) from 8.2 - 10. If I used that then it will be by the time I get the reaction started then it will be more basic in here (flask) than acid
No, because the range of methyl orange is 2.9 to 4.6. No I don't know. I could have used bromothymol blue because the pH range is from 6.0 to 7.6; When it's over 7 it changes to base, so if it's over 7 then it's O.K. But in acid it is yellow and when it's neutral it is green whereas this (phenolphthalein) is clearer or colourless in acid.

This range (for methyl orange) is too low. It's between 3.2 - 4.6. Bromothymol blue wouldn't be bad actually. The pH is higher but if it comes to choosing between these two I will choose this (phenolphthalein) but just from experience. I think I have done this before and we've used this (phenolphthalein) basically.

I don't think they (methyl orange and bromothymol blue) would have been effective because the colour change would have been at a different (lower) range. Methyl orange goes from 2.9 - 4.2 and I guess as we add the base it will change (colour) but for a short while.

This one (bromothymol blue) might be good too because the graph is steep and it's closer but just that I am used to using phenolphthalein in doing this reaction. I think it's easier to see it change to pink. This one (methyl orange) won't because it's lower, it's further from 7, the neutral point so that may be it will begin to change before the endpoint. It will probably be O.K. because it's such a steep graph but I don't know.

I think methyl orange will probably be too low. I am saying that phenolphthalein changes colour when it hits somewhere around 9, a pH of 9, if it's (the final solution) neutral at about 7. This methyl orange is lower (in pH range) than that (pH of 9) then it's not going to change. You could have used bromothymol blue but may not work as well as phenolphthalein. It probably might have worked but it's kind of low.

I guess you could (use methyl orange and bromothymol blue) Since they are all indicators if you know the colour change then you (can) use it.

No, if you using the base at the bottom (in the flask) then you use the others (phenolphthalein and bromothymol blue). The best to use in universal indicator, that way you know the range.
Q: I don't think methyl orange will be that effective because it changes to neutral at the pH level of 2.9 to 3.6 while the base we started with has pH level of 13. So probably the point of neutralization will be somewhere between 1 and 13. Like it won't be as low as 1. Since OH⁻ equals H⁺ ions I guess it would be very close to the centre, would be half of 13 so 6 - 7.6 is around that range. This (phenolphthalein), I guess you could use it, but it's a little bit high 8.2 - 10.0

R: No, I don't think so; I haven't used methyl orange before. I don't know, I used phenolphthalein last year but I can't tell.

S: I don't know.

T: It's possible but according to the range I wouldn't use methyl orange because its range up to 4.6 isn't high enough to determine where the two solutions are neutralized. The phenolphthalein has range above 7 and may not be very suitable.

U: No because that's what we did in the lab and that's what I know.

V: No because the other indicators (bromothymol blue and methyl orange) are for acids (that is when the base is in the flask and you want an acid solution).

W: This one (bromothymol blue) will start changing at pH of 6 so it wouldn't be completely neutralized yet; it's still slightly acidic. This one (methyl orange) only goes to 4.6 which is still acidic so I wouldn't know when it's neutral.

X: I couldn't have used methyl orange. I don't know why (but) I think you find the concentration of your base approximately the pH of the base so then you know approximately that the two kind of match. I decided not to use it (phenolphthalein) because I figure the pH of this base is 7 and phenolphthalein changes between 8 to 10.

Y: Well, I think I could use bromothymol blue but not the methyl orange (because) it will still change colour since pH goes to basic but I don't know what the colour is. But why use the unknown when you know the known.

Z: I guess the bromothymol blue will have been better because you get a solution that's around neutral instead of this one (phenolphthalein) which is more basic. It methyl orange) is for more acidic solution ... that has pH between 3.4 - 4.6 ... That is, if it was a strong acid and weak base then you have more acidic solution.
AA Yeah, I think so ... Well depending on what the pH of each indicator is ... the indicator gives you a clue of the pH of the unknown solution ... Since this (methyl orange) is an acid and this one (bromothymol blue) measures quite close to a base that is it's (bromothymol blue) is neutral so I couldn't have used it. I don't know if I could have used methyl orange ... I think I could have used methyl orange because it has a low pH and you're finding the concentration of acid so you have to have a pH that is low.

BB I could have used bromothymol blue because it's a bit basic. That's (that is, methyl orange) is more acid, I don't know.

CC Yes, it wouldn't really matter (to use phenolphthalein) I suppose (because) it's (the pH range is) close enough to 7 ... If you using a weak acid and strong base then you use phenolphthalein, pH is 8 - 10 and the salt is probably basic ... Probably not (methyl orange), it's (pH is) too low. I would use methyl orange if I was titrating with strong acid and weak base. The solution will probably .. definitely be acidic and this (methyl orange) is in the range.

DD No because first if we take methyl orange, the pH varies from 3.4 - 4.6; It means it is only used to indicate the ... pH of a solution between 3.4 - 4.6. If the pH of the solution is not 3.4 - 4.6 like this one (HCl + NaOH) when we add the indicator it doesn't change. I think we can use it (bromothymol blue) as an indicator because it is between 6 and 7.6. The resultant solution we suppose it should be zero, no it should be 7 after titration; the pH of this solution is 6 - 7.6 so I think we can use it. There will be colour change.

EE O.K. the methyl orange, the pH level is a little low so I don't think we can use that one. Maybe the phenolphthalein ... but since the pH is little higher so it might be out of range or something from the stoichiometric point.

FF Yes, you could use the other ones (bromothymol blue and methyl orange) too. It's the same indicator, just the pH vary, right?

GG If I don't know about these two, I won't use them because if I use this one (bromothymol blue and methyl orange), I don't know what will happen - I don't know when it will change, therefore I use this one (phenolphthalein)
(Student holds bromothymol blue in his hand) pH is 6.0 to 7.6. I would think so because this (bromothymol blue) would be more basic as compared to that (HCl) so I can still use it ... HCl is stronger, I think it's stronger than all 3 of these (indicators) so it is possible to use bromothymol blue and methyl orange.

II No because what this (phenolphthalein) does is say with pH of 8 to 10, and what it means is that when the pH of the liquid reaches this area it indicates a change but these (bromothymol blue and methyl orange) are quite low so we just use phenolphthalein. I am not sure why we were not told much about it.

JJ Methyl orange, you can't use it because it's (ph range) too far from zero, too far from 7. (Phenolphthalein) can be used because it's fairly close to 7.

KK Probably not (because) well, in the experiment in the lab we used phenolphthalein. It's pH is 8 - 10. The pH range for these (bromothymol blue and methyl orange) are lower.

LL I guess I could have used that (bromothymol blue). Methyl orange, the pH is too low. Because the base like the acid is very strong so it (pH at stoichiometric point) will be close to 7. It (bromothymol blue) starts to change at 7.6. Yeah, I guess I could have used it. It would have stopped me from overshooting.

MM ... No, I don't think this (methyl orange) will work because it's not really even close to 7. If it were to change colours, it will change colours while the solution is still acidic ... I would have thought this (bromothymol blue) would have worked because pH is around 7 the pH of water but it didn't (initially student tried to use bromothymol blue but then wasn't sure of the colour changes so used phenolphthalein instead).

NN No, they (methyl orange and phenolphthalein) wouldn't indicate the endpoint. One (phenolphthalein) is too high and one (methyl orange) is too low.

OO I am not sure but I think the pH (ranges) might be too low for both of them (methyl orange and bromothymol blue); I don't know.

PP No, you wouldn't use it in the lab to find out equal amounts of acid and base. I mean you wouldn't find equal amounts of each one (acid and base) if you use these (phenolphthalein and methyl orange). It wouldn't make sense since NaOH is a strong base and HCl is a strong acid; when they react together it's 1:1, O.K. That means 0.1 moles of acid will react with..1 moles of base, therefore producing water with pH 7 ... That (phenolphthalein), will give a basic solution because its high methyl orange is used for acidic type of solutions.
QQ Well, I could use bromthymol blue but I couldn't use methyl orange, it (methyl orange) has too low pH range. Well, bromthymol blue changes at 7 too but I just chose the phenolphthalein

RR We only use phenolphthalein, we didn't use the others. I guess they will work as well (because) they are indicators and they should do the same job

SS No, because when the endpoint is reached it (the pH) will be greater than 8, greater than 7

TT No since it changed within this range (pH 8 - 10) it won't change within the other ranges; because it took this amount of NaOH to neutralize HCl and that's when the colour changed

UU I am not too sure (about phenolphthalein and methyl orange) ... Like we did experiment and we run over and they say one jump could make a difference but this is a strong acid and a strong base; the titration curve I think goes like this (student draws the titration curve). It reaches a plateau so you can use wide range of pH (meaning indicators)
Terminology

Question:

21. What is the endpoint in a titration?

Responses:

A  I don't know
B  No, we didn't discuss that in class
C  I haven't heard about it but I'll guess and say the point when you have a neutral solution
D  It's the neutralization point. When it's neutral
E  That's when the colour changes and I wouldn't think it's the same as stoichiometric point
F  That's when the solution is neutralized
G  It's the point where the pH is neutral or 7
H  When you've got equal amount of moles of acid and base together and when you add an extra drop that's when the indicator is indicating it because it's basic
I  Endpoint is when there's the same number of $\text{OH}^-$ and $\text{H}^+$ molecules ... Endpoint is when the indicator changes to the other colour
J  When the number (of moles) of the known (base) are equal to that of the unknown (acid)
K  The endpoint is when the colour changes
L  When the $\text{OH}^-$ and $\text{H}^+$ in the solution are equal
M  When there's a change in colour
N  It's the change in colour
O  I don't know
P  Endpoint is when the solution changes colour
Q  Endpoint is the point where it's equal, it's neutral
R  No, I don't know
S  I haven't heard (of) it
T I haven't heard anything about that

U That's the point when you should have equal amounts of ions - basic and acid to form water

V It's where the acid and base are completely neutralized

W I think it's when the point, when the indicator is going to shift from showing one colour to another

X I don't know

Y Where the reaction of $H^+$ and $OH^-$ ion is complete, no excess $H^+$ ions

Z It's when the colour change appears. That's where the ... I don't know how to explain

AA ... That's before stoichiometric point. The point that tells you the first sight of change in colour of solution

BB When the base standardizes the acid - (that is) mix it so they are equal

CC That's when the indicator changes colour

DD (When) equilibrium is established, I mean the reaction is finished and it is neutral

EE That's when indicator changes colour to show you that the titration is even or something, like when the acid and base have neutralized

FF Oh, that's when it reached equilibrium and everything is ... I think that's when they're equal - the pH (of acid) and the pOH (of NaOH). I think that's it

GG I didn't read the book, so I don't know

HH When the HCl and NaOH react completely - when there's no more HCl in there

II When we have certain molarity of HCl and it reacts with certain molarity of NaOH. It tells this reaction (student points to equation for reaction) has occurred inside the solution and the solution is neutral

JJ It's when you go past where the concentration of both acid and base are equal

KK It's the same as stoichiometric point (i.e. where you've added equal amounts of base and acid)
LL  That's the indicator endpoint. It's the same, well, if it's the right indicator. (If not) then the indicator will change colour when it's not equal. Like the indicator changes when the pH is at a certain level and the stoichiometric point will be at a different pH level. I don't know

MM  That's the same thing as stoichiometric point (when all the base has neutralized all the acid)

NN  I think that's the same as the stoichiometric point for the titration (that is, where the number of moles of acid equals the moles of base)

OO  That's when you have added equal moles of base to equal moles of acid

PP  Endpoint is where the volumes - the moles of the two reactants are the same

QQ  That's when the colour changes

RR  The endpoint is when you have equal amount of base and acid

SS  Interesting, we had something about endpoint but I can't remember it

UU  When the colour changes
Question:

22. What is the stoichiometric point or equivalence point in titration?

Responses:

A. I don't know

B. I don't know

C. I am not familiar with these terms

D. I don't know, but I can guess that it is when the amount of OH and H\(^+\) are equal

E. When there's the same amount of OH\(^-\) and H\(^+\) ions

F. When the concentration of H\(^+\) and OH\(^-\) are the same

G. I don't know

H. That's the point when the moles are equal - just at the point when the moles are equal

I. That's when the amount of OH\(^-\) and H\(^+\) ions are equal

J. The number of moles of acid and base are equal

K. Stoichiometric point is when the number of moles between OH\(^-\) and H\(^+\) are chemically equivalent

L. When the solution is equal in H\(^+\) ions and OH\(^-\) ions

M. That's there's same number of moles of acid and base

N. Stoichiometric point will be when the moles of OH\(^-\) and H\(^+\) are equal

O. When it's equal - the acid and base

P. Stoichiometric point is when amount of acid and base is equal in concentration not in volume

Q. I don't know

R. I don't know

S. I think it's when all acid react with the base

T. It's the point at which the solution is neutralized

U. No, I can't recall
V No, I don't know what it is

W When there's same amount of $H^+$ as $OH^-$

X Should be the point at which the concentration, knowing that the $OH^-$ is .1 M, of the $H^+$ ion in the acid is the same (.1 M)

Y It's equivalent to it (that is where the reaction of $H^+$ and $OH^-$ ion is complete)

Z That's when the amount of the volume of acid is equal to the volume of base

AA It's the point at which the two solutions are in equilibrium to each other, equal

BB ... It's what I couldn't figure out in the test (class test given by the teacher). I don't know

CC It's just when the concentration of the hydronium ion is equal to hydroxyl ion

DD No, I don't know

EE It's the point where the hydrogen ions equal the hydroxyl ions in the chemical reaction

FF No, I don't (know what is is)

GG No, I don't know

HH I read about it but I forgot

II No, I don't

JJ Yeah, it's when the amount of acid ... It's when the concentration of $H^+$ ions equals concentration of $OH^-$ ions

KK It's the endpoint where you've added equal amounts of base and acid and at that point the colour should barely change

LL It's the point where you have equal amounts of, equal moles of hydrogen and hydroxyl ions

MM It's just when the amount of base equal the amount of acid

NN It's the point when all the acid or all the base has neutralized all the acid

OO It's the point where the number of moles of acid equals number of moles of base

PP It's when equal moles of acid have been added to base ...
QQ Stoichiometric point is where the ... it's similar to the endpoint but it's where the reaction is - it's when the base is ... I can't quite remember that

RR That is when equal amounts of the acid is added to the NaOH

SS Stoichiometric point is when you have equal amount of acid and base together.

TT Stoichiometric point ... there's something said about it, I think ... base reacts one to one with acid

UU It's the point when equal numbers of reactants are present
Question:
What happens to the HCl and NaOH in this titration?

Responses:
A They cancel each other, they neutralize to form H₂O and NaCl
B You're trying to get a neutral solution but I'm not sure of the products
C They neutralize, the pH comes out to 7 and NaCl and H₂O is formed
D They neutralize, and H⁺ and Cl⁻ and Na⁺ and OH⁻ are formed
E The OH⁻ and H⁺ form water and the other ions form salt
F Neutralize each other to form ...
G You get water and salt
H They combine - the hydrogen or protons are added from acid to the base into a salt and water
I They will neutralize to form H₂O and salt
J They neutralize each other to form salt and water
K You have salt and water
L As acid is added to base depending on the amount it turns neutral ... the product is water
M The hydronium and hydroxide ions react to produce water and the ions form salt
N If the moles of acid and base are equal then they will neutralize each other to form salt and water
O They neutralize each other ... I don't know the products
P They neutralize to form water and salt
Q The number of moles of OH⁻ and H⁺ are equal therefore they neutralize each other. The product formed will be NaCl and H₂O
R I don't know
H⁺ ions react with OH⁻ to form water. Na⁺ ions and Cl⁻ ions remain, they won't react together.

It will be neutralized ... NaCl salt and HOH which is water will be formed.

The OH⁻ ions combine with H⁺ ions to form water.

They form salt and water.

The H in HCl, the H⁺ and the OH⁻ from the NaOH combine to make water and the NaCl stays in solution.

You gonna form salt and water.

They form salt and water.

You get a salt and water.

Water, sodium ions and chloride ions are formed.

I don't know.

They form neutral salt mostly because it's strong acid - strong base and that's why I chose bromothymol blue.

It will form a salt and water.

You get NaCl and water.

You get sodium chloride and also water.

I think, the base will react with the acid and form water and salt.

What happens is the H⁺ ion combines with OH⁻ ion and forms water.

... Salt and water.

Water and salt are formed.

NaCl and H₂O are formed.

The hydrogen combines with OH⁻ ions to form water. The Na⁺ and Cl⁻ ions are bystanders. They don't get involved in the reaction.

Well, the H⁺ from HCl associates with the base, OH⁻ and the Na⁺ and Cl⁻ remain as free ions.

We know just the H⁺ ions react with the OH⁻ ions 1:1 and neutralizes it. The products are water and Na⁺ and Cl⁻ ions.
OO Sodium and chloride ions won't react; then you have the hydrogen ions going over to the hydroxide ions to give hydronium and it will be a 1:1 ratio

PP ... The H\(^{+}\) and OH\(^{-}\) come together to form water; the sodium and chloride ions, they don't do anything because they are by-standing ions in the solution

QQ You get water formed and Na\(^{+}\) ions and Cl\(^{-}\) ions

RR You get hydronium ions, Na ions and hydrogen

SS It forms water and the Cl\(^{-}\) and Na\(^{+}\) ions are left in solution

TT They will be neutralized and water, sodium and chloride ions will be formed

UU Water is formed and Na\(^{+}\) ions and Cl\(^{-}\) ions
APPENDIX M

INTERVIEW DATA FOR EACH SUBJECT ON

THE COMPUTATION PROBLEM
Summary of Results on Using Experimental Data in Computations*

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<th>NaOH:HCl</th>
<th>Acid:1 Base</th>
<th>NaOH:H₂SO₄</th>
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0 = Incorrect answer on NaOH : HCl
1 = Correct answer on NaOH : HCl
2 = Same as one calculated for HCl : NaOH
   a) Since volumes remain the same
   b) Mole ratio is 1:1
   c) Since the reactants are highly dissociated and the
      volumes used are the same
   d) Since HCl and H₂SO₄ are strong acids
3 = Twice as much as initially calculated concn. of HCl
   a) Ratio is 2:1 acid to base
   b) Ratio is 2:1 base to acid
4 = Half as much
   a) 2:1 acid to base
   b) 2:1 base to acid
   c) H₂SO₄ given 2H⁺ and NaOH given 1 OH⁻
   d) I don't know
5 = Other responses
   a) I don't know
   b) By my calculation
   c) Na₂CO₃ is a weaker base