A STUDY INVESTIGATING A HIERARCHICAL MODEL RELATING TO STOICHIOMETRIC CALCULATIONS

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by

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ABSTRACT

The purpose of this study is to identify and validate a learning hierarchy relating to stoichiometric calculations.

The sample consisted of 180 grade ten chemistry students and 57 grade nine general science students in four senior high schools. Following formation of a hypothesized hierarchy, two test instruments compounded from tests for skills represented in the hypothesized learning hierarchy, were administered to all subjects soon after instruction of the topic was completed by the teacher involved. In addition, an instructional booklet, which was intended to remediate for subordinate skills which subjects failed to learn during regular instruction, was administered to all of the students in the sample.

Three statistical tests, namely the White and Clark test of inclusion, the ordering-theoretic method and the Dayton and Macready method were used to analyze the data. In addition, a "test of transfer" was used to determine if transfer of learning existed between subordinate skills and related superordinate skills. The results of this analysis indicated that the hypothesized hierarchy was not found to be valid but an alternative hierarchy consisting of eight of the nine skills in the hypothesized hierarchy was considered valid in terms of the psychometric relationships between the component skills. One relationship existing between three of the lower skills in the alternative hierarchy seemed illogical and thus required further testing of the three skills concerned. Analysis of this additional psychometric data indicated that this relationship was incorrect, and that the relationship originally hypothesized for these three skills was correct. The alternative hierarchy was also considered valid, to a lesser extent, in terms of the learning transfer relationships between three of the upper skills comprising the alternative hierarchy. Learning transfer relationships for some of the skills in the alternative hierarchy could not be determined because of a limitation in the test of transfer applied.

The report concludes with a discussion of subjects' misconceptions relating to specific skills pertaining to attainment of the stoichiometric concept.

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Last, but by no means least, I wish to say thank-you to Gladys, my wife--who, while waiting very patiently for me many miles away and enduring many hardships which would have normally resulted in many couples going their separate ways, continued to inspire and support me throughout the past hectic, at times very frustrating, and yet immensely rewarding year.

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CHAPTER 1

THE PROBLEM

Introduction to the Problem

Educators have long been searching for a solution to the problem of how to identify optimal sequences of instruction. However, there is little agreement regarding how content should be sequenced.

Posner and Strike (1976) verify this when they indicate that very little information is available for describing the process used in organizing content and that no adequate prescription is expected in the near future. Based on this, Posner and Strike recommend that before one can answer the prescriptive question, "*How should content be sequenced?*" one must find the answer to the descriptive question, "*How can content be sequenced?*" In an attempt to answer the latter question, Posner and Strike propose a framework within which the many possible alternatives available for sequencing of content can be discussed, along with their implications for education. Five distinct categories of sequencing principles, namely, world-related, concept-related, learning-related, inquiry-related and utilization-related, each with a number of sub-categories, are suggested.

Shulman and Tamir (1973) note that the extensive influence of psychology on the development of science curricula has resulted in a diversity of science programs differing in scope, content and structure. However, they caution that psychology is too frail a base on which to support an entire curriculum. Shulman (1974) further expands on this when he suggests that the development of a psychology of school subjects should involve subject matter experts as well as psychologists, rather than primarily psychologists as has typically been the case.

Psychologists who have been influential in science curriculum development include Ausubel, Bruner, Gagné and Piaget. Gagné's suggestion that much of the curriculum content presented in schools may be best represented in learning hierarchies, was considered to be a promising model from which to attack the problem addressed in the present study, namely to determine an appropriate means to facilitate learning of one selected aspect of the mole concept, stoichiometric calculations.

Gagné's Hierarchical Model of Learning

Gagné's model and changes which have been made in it over the years are evident from the first to third editions of his book Conditions of Learning (1965, 1970, 1977). The original cumulative learning model (Gagné, 1965) represented the structure of any content to be learned by beginning with extremely simple levels of tasks, such as discriminations, and gradually progressing through more complex tasks through positive transfer of learning. Since then, many significant changes have become apparent. The third edition of Gagné's book reveals that emphasis upon hierarchies of learning as a description of how learning takes place is still the basis of his model, but restrictions have been placed upon hierarchies, particularly with regard to what kinds of content may be represented in learning hierarchies, and to the amount of content that may be covered by a hierarchy. His description of what constitutes a learning hierarchy has become clearer and more concise.

Gagné (1965) distinguished eight distinct types of learning which are hierarchically related and in which successive types are prerequisite to the learning of the next. This hierarchical model is illustrated in Figure 1. It should be noted that although all of the eight varieties of learning apply to school instruction, the four lower levels are considered applicable only to very young children. Signal learning, according to Gagné the very simplest form of learning, is not even included in the diagram.

This structure is retained throughout Gagné's writings. However, he now suggests (Gagné, 1972) that the components of this hierarchy represent only one of five domains of learning, and further that only this domain, the domain of intellectual skills, may be hierarchically represented. The other four domains include the learning of motor skills, verbal information, cognitive strategies, and attitudes. According to Gagné (1972) these domains require different conditions for learning. Also, the manner in which each develops is not identical. For example, it may be hypothesized that learners must understand the concepts mass and molar mass if they are to exhibit understanding of the relationship conveyed by the formula for finding the number of moles of a substance in a given mass of it. Learners who can apply their understanding of these concepts to a new problem may be said to possess the particular intellectual skill. The learner's approach to the problem represents his use of particular cognitive strategies. A statement of the formula for calculating the number of moles of the substance represents the use of verbalized knowledge. Manipulation of apparatus used in determining the mass of the substance involves the use of motor skills. The feeling the learner gets from his involvement

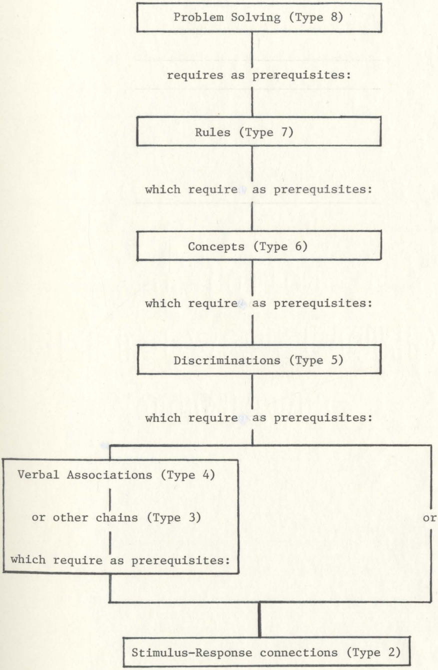


Figure 1. Gagné's (1970) representation of learning types.

with the subject represents the attitude domain.

Although each domain is recognized as being important in education, the importance of identifying hierarchies of intellectual skills cannot be emphasized enough, according to Gagné, because substantial development in each of the other domains requires the prior learning of relevant intellectual skills. Further, the domains of intellectual skills itself represents a large part of school learning.

Since its first conception (Gagné & Paradise, 1961) Gagné's hierarchical theory has been continually applied to problems in instruction and evaluation and by psychologists in studying sequences of cognitive and psychological development (Resnick, 1973). Three different conceptions of hierarchy theory have been developed in accordance with the theoretical backgrounds and interests of the investigators. The first two are related to the Gagnéan model, while the third relates to Piaget's work. They are described by Resnick as follows:

1. Learning psychologists and designers tend to define hierarchies in terms of asymmetrical transfer relationships between two or more tasks. Thus two tasks are considered to be hierarchically related if (a) one task is easier to learn than the other, and (b) learning the simpler task first produces positive transfer to learning the more complex task. For example, learning to count is demonstrably easier than learning to add.

2. Two tasks can also be said to be hierarchically related when (a) one task is more difficult to perform than the other, and (b) anyone who can perform the more complex task can reliably be expected to perform the simpler one.

3. Developmental psychologists have employed the concept of hierarchy to explain the occurrence of invariant sequences in the acquisition of concepts and logical structures as well as in physical and psychosocial development. "Stage" theories of development, such as Piaget's, are hierarchical theories in that they propose that an individual can reach a higher stage of development only by passing through a fixed series of lower stages.

An example of a learning hierarchy of intellectual skills for a science task is given in Figure 2. It is taken from a study by Wiegand (1969) which will be discussed in detail in chapter two.

According to Gagné (1962) a learning hierarchy should be developed by asking the question, "What must the learner be able to do if he is to achieve a particular new intellectual skill?" and then successively asking the same question for each new intellectual skill produced. The resulting hierarchy may be linear or branched, any branch implying that several skills may be considered directly prerequisite to the next higher one. Learning hierarchies generated in this manner represent what the learner should be able to do with respect to the skills, and are not concerned with learning in any of the other four domains.

It is then seen that a learning hierarchy has as its fundamental unit successive pairs of intellectual skills, one of which is subordinate to the other in the pair. The subordinate skill is identified as such because it is found to be necessary to and contribute to the learning of the superordinate skill (Gagné, 1970). For example, it may be hypothesized that a student attempting a new problem on calculating the number of moles of a substance must first understand the concepts mass and molar mass before he can manipulate them in the appropriate formula to find the number of moles of a substance. When the subordinate skills representing mass and molar mass have been mastered, learning of the related higher level skill is facilitated. If the subordinate skills have not been mastered, there will be no facilitation of learning of the higher level skill. Without this, two skills cannot be said to be hierarchically related.

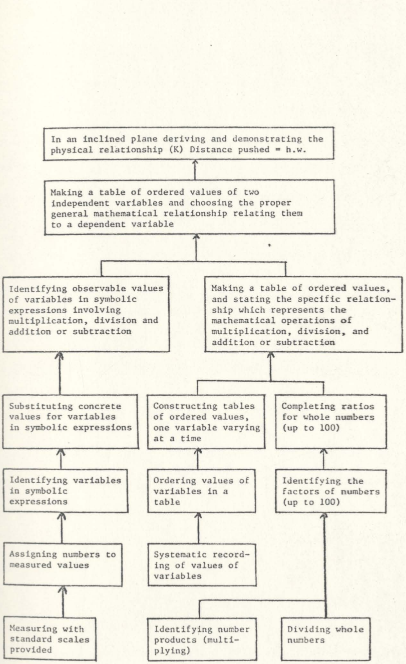


Figure 2. A hierarchy of subordinate skills applicable to the problem of deriving a general expression relating variables in an inclined plane (Wiegand, 1969).

In considering the amount of content suitable for inclusion in a learning hierarchy Gagné (1963) originally considered curriculum size units as appropriate. More recently Gagné (1974) suggests that the content of individual lessons seems appropriate. However, it may be suggested that such small hierarchies are unlikely to be of significant value to educators. As a result the question of what constitutes a minimum amount of content for inclusion in a learning hierarchy is not yet answered. The position taken with respect to the content under consideration in the present thesis is that a learning hierarchy should represent several lessons, as this will allow sufficient experimental control and also represent an amount of content sufficiently large for the hierarchy to be useful in classroom practice.

Alternative Hierarchy Theories

Ausubel's Theory. Two other major theoretical models, developed by Ausubel (1968) and Piaget (1964) have been of major importance to science education in recent years. Because they conflict with Gagné's theory in important respects they will be mentioned at this point.

According to Ausubel (1968) the most important factor which influences learning is what the learner already knows. However, for Ausubel the direction to be followed is from more complex to simpler ideas, whereas for Gagné the appropriate direction for learning is progression from simple to complex.

Central to Ausubel's theory is the distinction he makes between meaningful and rote learning. Meaningful learning is a process where new knowledge is related to relevant existing concepts or propositions in the learner's cognitive structure. Rote learning occurs when no relevant concepts are available in the learner's cognitive structure with which to associate newly learned knowledge.

According to Ausubel, meaningful learning occurs when the new knowledge interacts with the existing relevant concepts and is assimilated into these concepts. As a result, both the anchoring concept, which Ausubel refers to as a *subsumer*, and the new knowledge being assimilated are altered. Thus the process of meaningful learning results in a subsumption of new knowledge, or a further growth and modification of an existing subsumer. It is this interactive process which is at the core of Ausubel's assimilation theory of learning. As an individual acquires new knowledge through meaningful learning, prior concepts can be gradually subsumed into larger, more inclusive concepts resulting in concepts and propositions becoming more elaborate and new linkages forming between concepts. Where the cognitive structure of the learner does not contain available subsumers, Ausubel proposes that *advance organizers* can facilitate learning. In essence, organizers are introduced in advance of the material to be learned and are presented "at a higher level of abstractness, generality, and inclusiveness" than the content to be learned. The advance organizer then serves, in the place of relevant concepts which are not available, to anchor new learning, and leads to the development of a subsuming concept which can function to facilitate subsequent relevant learning.

As well as being different in the direction they perceive for learning, Gagné and Ausubel differ in what they consider to be of importance. For Gagné, the capabilities called intellectual skills are most important, while for Ausubel verbal learning is most important.

Gagné (1977) makes extensive acknowledgement of Ausubel's contribution to our understanding of the facilitation of verbal learning.

Piaget's Theory. Contrary to Gagné (1968) who contends that learning is prerequisite to development, Piaget (1964) contends that learning occurs as a function of intellectual development. Intellectual development, according to Piaget, involves the formation of a set of intellectual structures progressively constructed and differentiated by continuous interaction between the subject and the external world. These intellectual structures are developed as an individual progresses through four stages of intellectual development, namely, the sensori-motor, pre-operational, concrete-operational and formal-operational stages.

According to Piaget, progressive building of these structures occurs within each stage and, further, each stage builds upon the structures of the previous stage. In this sense Piaget's theory is a hierarchical theory.

Clearly, there are major differences and some similarities between the models described above. Some researchers (Strauss, 1972; Novak, 1977) do not believe they can be combined. Others (Beilin, 1971; Griffiths, 1979) suggest some combination be possible. The relative popularity of one over the others appears to be based upon theoretical persuasions rather than empirical evidence. There is a paucity of non-controversial empirical evidence, and studies comparing any of the models should be welcome to the research community at large at the present time. It is suggested that the present study should be seen in this light. It may be noted that it is part of a larger study (Griffiths, 1980) in which a number of science concepts are being examined simultaneously from the perspective of the Gagnéan and Piagetian models, respectively.

Definition of Terms

Chemistry Pretest: a test which tests the nine intellectual skills in the hypothesized hierarchy. It is composed of nine sub-tests of two items each. Each sub-test represents one of the intellectual skills in the hypothesized hierarchy. The 18 items are scrambled throughout the test.

Chemistry Posttest: a test identical in structure and purpose to the Chemistry Pretest, containing parallel items to those used in the Chemistry Pretest.

Gagné-type task analysis: deriving a hierarchy by asking the question "What must the learner be able to do in order to learn this new skill?" first on the terminal skill and then for each successive skill until a skill is reached which cannot reasonably be broken down further.

Instructional booklet: a written booklet containing instruction and test questions representing each intellectual skill in the hypothesized hierarchy. This booklet is reproduced in Appendix 7.

Intellectual skill: knowing how as contrasted with knowing that of information (Gagné, 1974, p. 55). Hence, application of knowledge is involved, rather than verbalization of it. For example, how to calculate the mass of one mole of calcium carbonate rather than simply knowing that it is 100 grams. The varieties of learning types represented in Figure 1 represent different kinds of intellectual skills.

Learning hierarchy: ideally, an arrangement of intellectual skills which are related to others in a subordinate-superordinate relationship, such that the subordinate skill in each pair is logically and empirically necessary for the learning of the superordinate skill and exhibits transfer of learning to the superordinate skill. In practice, hierarchies have generally been validated either in a psychometric sense, in which case no more than a small proportion of subjects exhibit any skill without being able to exhibit related subordinate skills, or in a transfer sense in which case learning of subordinate skills has been demonstrated to significantly enhance learning of related superordinate skills. In the present study both modes of validation are applied. The hierarchy validated as a result of the study will be reported in terms of both its psychometric and transfer characteristics.

Mole: the formal SI definition of the *mole* reads "the amount of substance which contains as many elementary entities as there are carbon atoms in 0.012 kilogram of carbon -12" (Heslop & Wild, 1975).

Stoichiometry: quantitative relationships between all reactants and products in a chemical reaction. In the present study only mass and mole quantities are considered.

Need for the Study

Historically, one of the major advances in the history of chemistry was the development of the laws relating weights of reactants and products. Today this is part of stoichiometry. An understanding and the correct performance of stoichiometric calculations is central to introductory chemistry courses. Moreover, it is typically integrally related to an understanding of the mole concept, one of the major underlying themes of modern high school chemistry courses.

Considering the importance of stoichiometry and its reliance upon the mole, it is of concern that it is a source of difficulty to many students. Duncan and Johnstone (1973), Hudson (1976) and Bleam (1981) indicate that pupils have difficulties in balancing and manipulating equations. Novick and Menis (1976) report that students cannot use the mole concept effectively in solving problems based on it. Johnstone, Morrison and Sharp (1971) report that students in the Scottish "O"-grade (16 year-olds) are not very confident with their ability to write equations and then carry out calculations based on them. Further, they report that in the Scottish "H"-grade (18 year-olds), students indicated that stoichiometric calculations was one of the areas with which they were having the most difficulty.

Educators have recognized this difficulty and as a result have applied a variety of approaches in their treatment of the mole and concepts such as stoichiometry, which are dependent upon it. A variety of approaches have been suggested. The application of algorithms such as the mole wheel (Head, 1968; Newstead, 1978; Ruda, 1978) or Williams' Triangle (Williams, 1977) are typical. Use is sometimes made of analogies (Bleam, 1981; Gabel & Sherwood, 1980). Others have suggested the use of general remediation (Chiappetta & McBride, 1980), a graphical approach (Hudson, 1976), or a methodology harmonizing with Piagetian theory (Rowell & Dawson, 1980). Within the various texts used by the students in the present study the mode and depth of treatment varies considerably.

Apart from the successful approach reported by Rowell and Dawson (1980), which enabled year 11 Australian students, including those initially mismatched to the task, to gain the necessary skills and knowledge to understand the mole and its applications in chemical calculations, the other varied approaches have not met with substantial acclaim. Smith (1978) suggests that the use of mole wheels does not lead to understanding. Gabel and Sherwood (1980) report that the use of analogies did not result in greater achievement. Chiappetta and McBride (1980) indicate that general remediation was not effective. Some authors (e.g., Hudson, 1980) recommend delaying the teaching of the mole, and implicitly stoichiometry. Clearly there is disagreement on whether and how the mole and stoichiometric calculations should be taught in introductory chemistry courses. Hence, there is a need for further research in this area.

One potential answer to the problem lies in the application of learning hierarchy theory. This, in turn, raises a second need. As will be demonstrated in chapter two, few well validated learning hierarchies in science exist. Hence, it is desirable to attempt to articulate the learning hierarchy model by attempting to identify further learning hierarchies. Stoichiometry appears to be a potential candidate for this. The present study attempts to meet both of the above needs.

Purpose of the Study

The purpose of this study is to identify a learning hierarchy for the concept stoichiometry. It is not suggested that it is possible to identify only one such hierarchy. What is suggested is that it is possible to hypothesize such a hierarchy by the application of a

Gagné-type task analysis procedure, and that this hierarchy or a modification of it may be validated in terms of its psychometric and transfer characteristics.

Research Questions

Question 1: Does the arrangement of intellectual skills represented in the hypothesized hierarchy represent a learning hierarchy which is valid psychometrically?

If the answer to question one is negative, question two will be considered.

Question 2: Does some other arrangement of some or all of the intellectual skills represented in the hypothesized hierarchy represent a learning hierarchy which is valid psychometrically?

The third research question relates to the identification of transfer of learning between the skills tested.

Question 3: Is significant transfer of learning evidenced between subordinate skills and related superordinate skills in the hypothesized hierarchy?

The fourth question relates to the identification of any misconceptions which students may exhibit for the skills represented in the hypothesized hierarchy.

Question 4: What common misconceptions do students exhibit for the skills represented in the hypothesized hierarchy?

Delimitations of the Study

Restriction of the sample to one grade level (Grade Ten) within the St. John's area represents an important delimitation. It is possible that different students in a different situation may respond differently, although there is no particular reason to believe this.

The restriction of this study to stoichiometry is another delimiting factor. Any superiority of the learning hierarchy model as a guide to the learning of science concepts may not be generalizable to other concepts in science. Further, it is possible that the particular learning hierarchy hypothesized might be deficient with respect to the inclusion of particular skills. Hence, the skills would be absent in the "validated" hierarchy. Hopefully, consultation with teachers and science educators eliminated this problem.

The particular test items represent another delimitation as they were designed for the study by the author. Although, as will be indicated in chapter three, every effort was made to ensure good content and construct validity and good reliability, it is possible that other items could very well have been used which would yield different results.

Limitations of the Study

A limitation exists in the fact that the investigators had no control over the sample selection apart from choice of schools. The sample represented a relatively narrow-academic range which tended towards high ability. A wider range of sample would have been useful, because in testing for hierarchical relationships a substantial variation of performance for each skill is desirable.

Another limitation is present in the procedure used to remediate any subordinate skills students may have missed. Although, as noted in chapter three, instructional booklets which indicated the missed subordinate skills were given to each student, there was no control over whether the remediation was done or not. As the intent of the instructional booklet, in conjunction with the Chemistry Posttest, was to provide evidence of transfer of learning, the desired transfer effect may be lessened.

Finally, the instruments used in the study represent a limitation. Ideally, except for spurious mistakes, subjects should get both items for a skill correct or incorrect. However, perhaps because individual items representing the same skill may not be identical in structure or presentation, some variation in response pattern was evident.

Summary

The general problem of sequencing of content has been discussed and a model of sequencing derived from Gagné's hierarchical model of learning has been proposed as a solution to overcoming difficulties students have when learning the stoichiometric concept.

Overview

The chapter which follows first considers a description and discussion of the essential features of the most important techniques which have been used to identify learning hierarchies, and considers in more detail three recent methods which were applied in the present study. It concludes with a description of empirical studies relating to hierarchies in science instruction. Chapter three presents the design of the study and a description of the test instruments and procedures. Chapter four describes the analysis of data and the results obtained from the study. The final chapter includes a summary of the study and the major conclusions and recommendations for further research.

CHAPTER 2

RELATED RESEARCH

Methods Used to Validate Learning Hierarchies

Bergan (1980) indicates that there are two major hypotheses related to the learning hierarchy model. These are consistent with what Gagné (1977) refers to as the two essential characteristics of a learning hierarchy. The first hypothesis to which Bergan refers is the prerequisite skills hypothesis. It holds that learning hierarchies are composed of intellectual skills arranged such that each subordinate skill is prerequisite to the skill(s) immediately above it in the hierarchy. It assumes that each subordinate skill in a hierarchy is necessary to successful performance of the skill above it.

The second hypothesis to which Bergan refers is called the positive transfer hypothesis. It holds that prerequisite skills mediate transfer for the superordinate skills to which they are related. It assumes that if one skill is prerequisite to another, mastery of the prerequisite skill will contribute substantially to the learning of the related superordinate skill. It was based upon this hypothesis that Gagné (1961) derived the concept of positive transfer of learning for which he produced an index of proportion positive transfer.

In their early studies Gagné and his colleagues (Gagné, 1962; Gagné & Paradise, 1961; Gagné, Mayor, Garstens & Paradise, 1962) used the prerequisite skills and positive transfer hypotheses in hierarchy model validation. Unfortunately, as White (1973) notes, these learning hierarchies which were based upon Gagné's methods generally had faulty designs. Almost all of the studies suffered from one or more of the following weaknesses: small sample size, imprecise specification of component elements, the use of only one question per element, and the placing of the tests at the end of the learning program or even omission of instruction altogether. According to White, these flaws and the lack of a test of hierarchical dependence which takes account of errors of measurement meant that no meaningful quantitative conclusion could be reached about the validity of even one step in any hierarchy derived to that time.

White (1974a) further notes that the Gagné and Paradise (1961) index of proportion positive transfer proved to be unsatisfactory. The index was not useful because it could take values close to zero even if there was no hierarchical relationship between the skills or if they were independent of one another. Also, the index takes no account of errors of measurement and lacks a sampling distribution. Thus it was not an adequate test of the prerequisite skills or positive transfer hypothesis.

Other indices which have been used to determine whether each connection in a learning hierarchy was valid or not have also been shown to be unsatisfactory by White (1974a). When he applied three of the major indices suggested by Gagné and Paradise (1961), Walbesser and Eisenberg (1972) and Capie and Jones (1971) to the same set of data he obtained very different results.

White (1974a) also indicated that Guttman's (1944) coefficient of reproducibility, which assessed the fit of the hierarchy as an integrated whole had to be rejected because one incorrect connection could lead to the rejection of the whole hierarchy. Further, the method could only be used for linear hierarchies or composites of linear portions of hierarchies.

Such faulty designs and inadequate statistical techniques resulted in any new or existing findings being questioned. As a result some better measures which take account of at least some of these faults were necessary. In an attempt to do so White (1974b) made the following recommendations for improvement in the identification and validation of learning hierarchies:

1. Define in behavioral terms the element which is to be the pinnacle of the learning hierarchy.

2. Derive the hierarchy by asking Gagné's question (What must the learner be able to do in order to learn this new element, given only instruction?) of each element in turn, from the pinnacle element downward. Include all connections that seem reasonable, since the validation process can only destroy postulated connections, not create them. Avoid verbalized elements as they can be included in the instructions.

3. Check the reasonableness of the postulated hierarchy with experienced teachers and subject-matter experts.

4. Invent possible divisions of the elements of the hierarchy, so that very precise definitions are obtained.

5. Carry out an investigation of whether the invented divisions do in fact represent different skills. One way of doing this is to write two or more questions for each division and give them to a sample of Ss. Wherever any subjects are observed to answer correctly the set of questions for one division, while answering incorrectly the set for another, the divisions are taken to be separate skills. White has given a description of the practical arrangement of such an investigation.

6. Write a learning program for the elements, embedding in it test questions for each element. The questions for an element should follow immediately after the frames that teach the element. There must be two or more questions for each element to allow for an estimate of their reliability.

7. Have at least 150 Ss, suitably chosen, work through the program, answering the questions as they come to them.

8. Analyze the results to see whether any postulated connections between elements should be rejected. A suitable test of hierarchical relationship has been developed by White and Clark. The hypotheses compared in the test are Ho: the proportion of the population from which the sample was drawn who can learn higher elements without the lower element is zero. The test provides estimates of the probabilities of the observed results given that Ho is true or given specific values of the proportion under Ha.

9. Remove from the hierarchy all connections for which the probability under Ho is small, say 0.05 or less.

One aspect of the above model requiring further elaboration is the test of inclusion (White & Clark, 1973). This method, as well as others, will be discussed in the next section.

White is of the opinion that these changes should lead to a sound basis for both the design and validation of future learning hierarchies. Griffiths (1979) argues against White. He maintains that White's model is lacking in several respects. First, Griffiths maintains that the White and Clark test represents a psychometric approach to hierarchy validation. According to Griffiths any hierarchy validated in this manner does not necessarily imply transfer to greater learning of the superordinate skill(s). Second, Griffiths argues that White's recommendation of a programmed instruction format restricts the applicability of the learning hierarchy to only one mode of instruction and that if there is a generalized hierarchy its structure should exist for other modes of instruction. Third, Griffiths suggests that the testing of subordinate skills should be carried out after as well as during the instructional period, and that the primary psychometric test be made on the former, which is also consistent with a more recent opinion of White (1976). Finally, Griffiths recommends the use of a test of positive transfer as well as psychometric validation.

Although White recommends the use of his test of inclusion (White & Clark, 1973) other procedures exist for empirical validation of hierarchies. Griffiths and Cornish (1978) have grouped the methods which have been used to validate learning hierarchies into two classes, those which reflect the transfer properties of hierarchies and those which reflect the notion of a relatively inviolate sequence, respectively. The authors concentrate on several methods of the second group, namely, the 'ordering-theoretic' method (Bart & Krus, 1973; Airasian & Bart, 1975), the 'test of inclusion' (White & Clark, 1973) and a method suggested by Dayton and Macready (1976). More recently, a new method incorporating structural modelling techniques (Bergan, 1980) has been suggested whereby latent structural analysis and path analysis have been advocated for testing prerequisite relations and positive transfer, respectively. The first two methods discussed by Griffiths and Cornish focus upon comparisons of pairs of skills while the third method and that described by Bergan consider the hierarchy as a whole. This study will consider in detail the first three methods. It was felt that the use of these methods and a suitable test of transfer would be more than adequate to validate a learning hierarchy. The question of transfer and the role it plays in the validation of a learning hierarchy will also be discussed in detail.

The Ordering-Theoretic Method

In the ordering-theoretic method, the validity of a hierarchy is determined by considering the relationship between pairs of elements. The contingency table in Figure 3 will help to explain the operation of this method. In this table 1 denotes possession and 0 denotes

		UPPER SKILL	
		0	1
LOWER SKILL	1	B	A
	0	C	D

Figure 3. Data matrix for the "ordering-theoretic" method.

non-possession of a skill, while the letters A, B, C, D represent the observed frequencies in the appropriate cells. High A and C values tend to be supportive of a hierarchical relationship, while high D values tend to deny the relationship. The "ordering-theoretic" method focuses upon whether an arbitrary prespecified tolerance level for D is exceeded. If it is, no hierarchical connection is considered to exist.

This test is applied to all possible combinations of pairs of skills in the hierarchy, from which a composite hierarchy is identified. Griffiths and Cornish (1978), however, note that this method is deterministic, and does not take into account errors of measurement. No test is provided to determine the statistical confidence with which each identified hierarchical relationship can be claimed to exist.

A further problem likely to confound the results of applying ordering-theory is described by Wellens, Lenke and Oswald (1977). These authors note the current unresolved debate about the assessment cut-off scores for mastery and show that different "recommended" criteria for mastery may result in quite different hierarchies.

While the above is true for the ordering-theoretic method and most other methods, it does not apply to the test discussed in the next section.

The White and Clark Test of Inclusion

The basis of the White and Clark (1973) test of inclusion is to determine whether the subjects possessing a hypothesized subordinate skill represent a sub-set of the subjects possessing a hypothesized related superordinate skill. By using two or more test items per skill allowance may be made for errors of measurement. Figure 4 shows a typical matrix

SKILL II (UPPER) QUESTIONS CORRECT

		0	1	2
SKILL I (LOWER) OUESTIONS CORRECT	2			
	1			
	0			

Figure 4. Data matrix for the White and Clark test.

for two items per skill. The cell representing a score of zero on the lower skill and the maximum possible (2 in this case) on the upper skill, referred to as the critical cell, is used to test the hierarchical relationship. This cell is assumed to contain those subjects most likely to possess the upper skill and lacking the lower one. The basis of this method is to test the null hypothesis that there will be no entries in the critical cell, other than those representing errors of measurement. The probability that the observed frequency does not violate the null hypothesis is calculated by using the marginal totals. For the case of two questions per skill the probability that a member of the sample will be found in the critical cell is

$$P_{02} = P_o(1-\Theta_b)^2\Theta_d^{\,2} + P_I(1-\Theta_a)^2\Theta_d^{\,2}2 + P_{II}(1-\Theta_b)^2\theta_c^2 + P_B(1-\theta_a)^2\theta_c^2$$

where

P_o = the proportion of the population with neither skill.

P_B = the proportion of the population with both skills.

P_I = the proportion of the population with skill I only.

P_{II} = the proportion of the population with skill II only.

Θ_a = the probability of someone with skill I answering correctly any skill I question.

Θ_b = the probability of someone without skill I answering correctly any skill I question.

Θ_c, Θ_d = are the corresponding probabilities for skill II.

To make the estimate of P_{02} as large as possible and hence reduce the probability of type I error, Θ_b is assumed to be zero and Θ_d is assumed to equal one. That is, it is assumed that all subjects with one skill I question correct really possessed skill I and all those with one skill II question correct lacked the skill. Modifications can be made to the derivations above to accommodate three questions per skill. In each case the hierarchical nature of all pairs of connected skills in a hypothesized hierarchy is tested, and the validity of the composite hierarchy then judged.

It should be noted that the same procedure can be used with any designated percentage exceptions in addition to those representing errors of measurement. Examples of such application include Linke (1975) and Beeson (1977). The result of such application are hierarchies of substantial rather than absolute levels of hierarchical dependence. The White and Clark test does not consider the hierarchy as a whole. The method discussed below is capable of doing so.

The Dayton and Macready Model

The basis of the Dayton and Macready model (Dayton & Macready, 1976) may be traced to Guttman (1944). Although he was not concerned with learning hierarchies, the simplest type of learning hierarchy (i.e., a non-branching, linear pattern) represents the form of a Guttman scale. For a perfect hierarchy (scale) no subject should exhibit a later skill if he fails to exhibit any earlier skill. Such responses constitute error. To maintain some standard for acceptance or rejection of the scale, and at the same time allow for some reasonable level of error, Guttman derived an index of "reproducibility." This was defined as the quotient of total errors (i.e., deviations from a perfect scale) over total responses, subtracted from one. Arbitrarily, a reproducibility of at least 0.90 was declared necessary if the hypothesized scale was to be considered valid.

Lingoes (1963) criticizes Guttman's method for several reasons. First, it is limited to linear scales or combination of linear scales and, second, the statistical tests are arbitrary. Proctor (1970) suggests them to be pre-statistical, and describes a method designed to elevate scaling to a better statistical foundation. Although Proctor's method has not been directly applied in validation of learning hierarchies, it forms the basis for Dayton and Macready's (1976) intent to overcome the other main objection to Guttman scaling. That is, the Dayton and Macready method offers the possibility of extension to hierarchies of any configuration. Essentially then, the Dayton and Macready model can be used to assess the goodness of fit of a hierarchy, whether it be linear or branched, to the data. It also permits, if necessary, a statistical comparison between two or more alternative hierarchies which are fitted to the same data.

In order to discuss how Dayton and Macready's validation procedure can be used to accomplish these objectives, it is first necessary to point out that data for the validation procedure is collected by having subjects complete items which test the skills in the hypothesized hierarchy, and then score these items dichotomously. Data from any subject collected in such a manner is then summarized in the form of a column vector "u" comprised of 0's and 1's (where 0, 1 represent non-possession and possession, respectively, of a skill and the hypothesized lowest skill in the hierarchy is the first element and the highest skill is the last element in the vector).

As a hypothesized hierarchy of skills already exists, a set of distinct pattern (or response) vectors "V_j" can be determined for it by the investigator, each of which is comprised of 0's and 1's, and which as a set defines the possible response patterns for the skills as they are arranged in the hypothesized hierarchy.

As an example consider the case of a strictly linear hierarchy composed of four skills for which one item is used to test each skill. There are only five distinct pattern vectors which are true to the hierarchy. They are $V_1 = (0\ 0\ 0\ 0)$, $V_2 = (1\ 0\ 0\ 0)$, $V_3 = (1\ 1\ 0\ 0)$, $V_4 = (1\ 1\ 1\ 0)$ and $V_5 = (1\ 1\ 1\ 1)$. All of these patterns indicate that a correct response on an upper skill in the hierarchy is only possible after a subject has obtained correct responses on all lower skills subordinate to it. It is quite possible that subjects will exhibit pattern vectors which are not one of the five valid ones above. Such invalid responses are not true to the hierarchy and as such are referred to as misclassifications.

In order to apply the above reasoning to a non-linear hierarchy consider the two branched hierarchies represented in Figure 5. Each hierarchy contains five skills, but as can be observed these five skills are arranged differently in (a) and (b). As a result, these hierarchies will not have the same number of, or the same distinct pattern vectors. In (a) ten distinct pattern vectors (0 0 0 0 0), (1 0 0 0 0), (1 1 0 0 0), (0 0 1 0 0), (1 0 1 0 0), (1 1 1 0 0), (0 0 1 1 0), (1 0 1 1 0), (1 1 1 1 0), and (1 1 1 1 1) are true to the hierarchy. In (b) there will only be seven true pattern vectors, namely (0 0 0 0 0), (1 0 0 0 0), (0 1 0 0 0), (1 1 0 0 0), (1 1 1 0 0), (1 1 1 1 0), and (1 1 1 1 1). All other patterns which one could determine for these two hierarchies and which a subject could give as a response would be considered misclassifications.

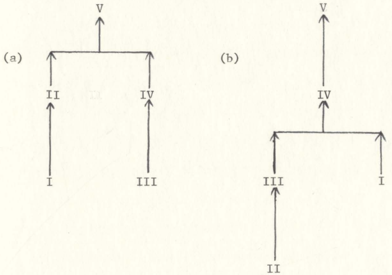


Figure 5. Sample hierarchies for the Dayton and Macready model.

It is possible that the data from some subjects may be in error as a result of the subjects guessing the answer to an item or forgetting how to do an item, and therefore getting a correct response when it should have been incorrect, or vice versa. To account for this Dayton and Macready capitalize on a suggestion used by Proctor (1970) in his scaling method. Effectively this results in it being possible to allow separately for a "1 - for - a - 0 - error" and a "0 - for - a - 1 - error." These they call "guessing" and "forgetting" parameters, α and β, respectively, although too much should not be made of the literal meaning of these terms. These parameters represent the probabilities that a subject will produce a response on some skill which is incompatible with the hypothesized hierarchy. For example, consider a subject who obtained a "1" on some item representing a skill when, according to the hierarchy, he should have obtained a "0". This subject would then be included in the α parameter. Similarly a subject who obtained a "0" when he should have obtained a "1" would be included in the β parameter.

Using Dayton and Macready's (1976) notation it is now possible to give their general probabilistic model for hierarchies. In its most general form the probabilistic model may be written as

$$\text{(i)} \qquad P(u) = \sum_{i=1}^{q} P(u|\nu_j)\Theta_j$$

where

$P(u)$ is the probability of a subject producing a specific column vector "u" if the hierarchy is valid.

Θ_j represents the probability that the j^{th} true pattern vector occurs; that is the hypothetical population proportion of respondents which achieves level j of the hierarchy.

V_j represents the set of q distinct pattern vectors, V_j,

and

$$\text{(ii) } P(u|\nu_j) = \prod_{i=1}^{k} \alpha_i^{a_{ij}} (1-\alpha_i)^{b_{ij}} \beta_i^{c_{ij}} (1-\beta_i)^{d_{ij}}$$

To explain the meanings of the elements in the second equation let g_{ij} be the i^{th} element in $V_j - u$, then a_{ij}, b_{ij}, c_{ij} and d_{ij} can be defined as follows:

$$a_{ij} = \begin{cases} 1 \text{ if } g_{ij} = -1 \\ 0 \text{ otherwise} \end{cases} \qquad b_{ij} = \begin{cases} 1 \text{ if } g_{ij} = 0 \\ 0 \text{ otherwise} \end{cases}$$

$$c_{ij} = \begin{cases} 1 \text{ if } g_{ij} = 2 \\ 0 \text{ otherwise} \end{cases} \qquad d_{ij} = \begin{cases} 1 \text{ if } g_{ij} = 1 \\ 0 \text{ otherwise} \end{cases}$$

The above definitions of a_{ij}, b_{ij}, c_{ij} and d_{ij} represent the corrections necessary to fit all of the distinct pattern vectors to an observed pattern vector; b_{ij} and d_{ij} represent the number of correct responses in each case and a_{ij} and c_{ij} represent the number of incorrect responses in each case.

The product of these overall response patterns is equation (ii). It is obtained by first raising the values of the misclassification parameters α and β to a power representing the number of "guessing" (a_{ij}) and "forgetting" (c_{ij}) corrections, and then multiplying this by the responses which are not misclassifications, (($1 - \alpha_i$) and ($1 - \beta_i$)) raised to a power representing the number of correct response in each case, that is b_{ij} and d_{ij}, respectively. If the product obtained from this equation, $P(u|\nu)$, is then multiplied by the probability that the

j^{th} true pattern vector occurs (Θ_j), and then summed for all true pattern vectors one obtains equation (i), and therefore Dayton and Macready's general probabilistic model.

In discussing the use of their model, Dayton and Macready indicate that a number of restricted forms of the probabilistic model have been identified because of their usefulness in applied situations. The actual restrictions are placed on the values of the "guessing" and "forgetting" parameters, α and β, respectively. Three types of restrictions, referred to as case A, case B and case C, respectively, are discussed by the authors. In case A, α and β are defined as given above in the general probabilistic model (that is, unrestricted). In case B equal "guessing" and "forgetting" parameters are assumed (i.e., $\alpha_i = \alpha$ and $\beta_i = \beta$ for all i). In case C a single error parameter is assumed (i.e., $\alpha_i = \beta_i \quad \alpha$ for all i).

If these restrictions were interpreted in terms of the precision of the misclassification parameters, α and β, it is seen that case B is more precise than case C, and as such warrants that it be used instead of case C. Further, it should be seen that case A could be used over either B or C since the misclassification parameters are unrestricted. In practice this is not possible because case A has only been solved so far for what the authors label as concept attainment models, which they define as models in which each subject responds completely correctly or completely incorrectly to a given set of items. As such this model is not of general use in validating a hierarchy because subjects do not respond in the matter described above. Therefore, the most appropriate application of Dayton and Macready's model, and the one which is utilized in this study, is case B.

In case B, as with the other two cases, maximum likelihood estimates of the various α's, β's and Θ's are obtained through a series of iterations. These values are used to compute the number of expected responses for each possible response pattern. The goodness of fit between data and hierarchy model is then calculated by both a Pearson chi-square test and a likelihood ratio expressed in the form of a chi-square. The latter appears to be more useful as it is less severely distorted by small frequencies, an important advantage when it is realized that for all except very small hierarchies a large proportion of the expected frequencies should be nearly zero if the hierarchy is valid.

Advantages and Disadvantages of the Three Methods

The White and Clark test and the ordering-theoretic method suffer from the disadvantage that they can only consider hierarchical connections between pairs of skills. From the results of these comparisons a composite hierarchy is produced. Such a procedure is less satisfactory than if the hierarchy could have been considered as one entity. For this reason, of the three methods discussed, the Dayton and Macready model is considered conceptually the most pleasing, for it considers the hierarchy as a whole--or at least in larger pieces than pairs of elements, and also offers a maximum likelihood procedure to test goodness of fit between model and data. However, it has several important disadvantages. First, the computer program which is essential to its application can only accommodate small hierarchies at present. Second, incorrect response patterns are accommodated to the hierarchical model by means of a guessing parameter common to all elements in the hierarchy and a forgetting parameter similarly common to all elements in the hierarchy. The estimated values of these two parameters affect the predicted frequencies of all response patterns, thereby diminishing the potential precision of the model.

Of the two methods involving comparisons of pairs of skills, the White and Clark (1973) test of inclusion is easily the more sophisticated. Although Dayton and Macready claim that their model subsumes that of White and Clark, and that the latter is equivalent to their case A, their claim is misleading in practice, because Dayton and Macready have solved case A only for the concept attainment model. Rather than being subsumed by the Dayton and Macready model, the White and Clark test has the advantage of effectively having a guessing and forgetting parameter for each skill. This avoids the problems caused by the use of common misclassification parameters in case B and case C of the Dayton and Macready model. Finally, Dayton and Macready correctly note that the White and Clark test is limited to equal numbers of questions per skill and to no more than three questions per skill. This limitation has been overcome by Griffiths and Cornish (1978) who have generalized the White and Clark test to any number of questions per skill.

While the "ordering-theoretic" method is much simpler to use and has been applied in several studies it is conceptually less pleasing than the probabilistic White and Clark test. The ordering-theoretic method, being deterministic, does not take into account errors of measurement and provides no test to determine the statistical confidence which can be attached to the existence of each hierarchical relationship.

Griffiths (1979) notes that because neither the White and Clark test nor the ordering-theoretic method consider the hierarchy as a whole, it is possible that in combining the results of analyzing the skills in pairs a different hierarchy may be arrived at than when the hierarchy is considered as a unit. Further, he notes that the validation of a hierarchy as a whole would seem to be a more acceptable procedure because in subsequent applications the whole hierarchy is more likely to be used.

Because the Dayton and Macready scaling model allows testing of complete hierarchies of any configuration, in the present study it will be used to test the hypothesized hierarchy, or an alternate of it, produced from the results of applying the White and Clark test and ordering-theoretic method to the data. The Dayton and Macready test is considered to be the primary test of the validity of the hypothesized hierarchy or alternatives to it.

The Question of Transfer

It has been indicated that the index of proportion positive transfer is conceptually pleasing but practically limited (White, 1973). Although the index has been dismissed, the concept of positive transfer is still useful. Glaser and Resnick (1972) point out that a hierarchy validated according to psychometric procedures carries with it no guarantee of positive transfer from subordinate to superordinate skills. Carroll (1973) considers transfer to be the essential criterion of the validity of a learning hierarchy. Gagné (1974) continues to emphasize the importance of positive transfer. White and Gagné (1974) express the opinion that a hierarchy validated by means of a test of transfer is more definitive than psychometric validation. Phillips (1974) notes that in general the notion of positive transfer through provision of learning hierarchies is supported by substantial evidence. Cotton, Gallagher and Marshall (1977) express an opinion similar to that of White and Gagné (1974). Bergan, Karp and Neumann (1979) report findings that are congruent with Gagné's (1962) assertion that prerequisite skills mediate positive transfer for superordinate skills. Bergan (1980) and Bergan and Jeska (1980) indicate that the demonstration of transfer is critical to the validation of a learning hierarchy, and recommend that hierarchical sequences should be validated by both a psychometric test and a test of transfer.

Despite these strong opinions of the importance of testing for transfer, many investigators have chosen to ignore Gagné's vertical transfer hypothesis and instead focused upon his prerequisite-skills hypothesis using a psychometric test. Knee and White (1979) suggest that the reason for this stems from the fact that the transfer method of validation is, as they refer to it, very cumbersome. Hence, most investigators use a psychometric test because it is much easier to implement.

Some investigators indicate that the concept of positive transfer can be expressed in other ways. Okey and Gagné (1970) did so by comparing the achievement of a group taught through the hierarchy with a group not so taught. Griffiths (1979) indicates that in theory the most satisfactory means of testing for positive transfer appears to be direct comparison of randomly assigned groups of students taught by following the hierarchy with a similar group taught without the use of the hierarchy, or even taught by a deliberately scrambled hierarchy.

However, he notes that the latter poses potential ethical problems, and suggests the alternative of comparing a group needing and given remediation in accordance with the hierarchy to a similar group which has not received remediation. Others (Bergan, Karp & Neumann, 1979; Bergan, 1980; Bergan & Jeska, 1980) suggest that structural equation techniques, in particular path analysis, can be used to determine the extent of vertical transfer.

The present author believes that both the psychometric and transfer definition of hierarchical dependency are of sufficient importance that a hierarchy validated by either but not both approaches should be regarded as incompletely validated. Griffiths (1979) provides the best rationale for this when he comments:

> The fact that it can be shown empirically that one skill (say B) is not learned without prior learning of another skill (say A) does not necessarily mean that learning A helps a group of individuals to learn B. Conversely, a significant positive correlation between the learning of two skills does not mean that the learner must master A first. However, if it can be reliably demonstrated that B cannot be learned until A is learned, and that learning B is associated with prior learning of A, then it can be claimed more legitimately that the skills are in hierarchical relationship to one another. (p. 66)

This view is taken in the present study. As a result, not only will the psychometric tests discussed earlier be used to validate the hierarchy, but also Griffiths' (1979) test of transfer, which is described in chapter three, will be used.

Learning Hierarchies in Science

Studies comparing the learning hierarchy and development models. Several researchers have investigated development hierarchies derived from Piaget's writings (Kofsky, 1966; Allen, 1970; Phillips, 1971; Raven, 1972; Robertson & Richardson, 1975). These will not be further described because they represent developmental rather than learning hierarchies.

Several other studies have been reported which set the developmental and learning hierarchy models in opposition with respect to the same concept (Raven, 1968; Wiegand, 1969; Bass & Montague, 1972; Griffiths, 1979; Murray, 1981). These studies will now be described briefly, and this review will then be followed by a section dealing with learning hierarchies relating to science instruction and particularly to chemistry.

Raven (1968) examined the development of the concept of momentum in children between five and eight years of age. In doing so he compared the appropriateness of a developmental hierarchy and a learning hierarchy as models of the development of the concept of momentum. According to the developmental hierarchy, derived by Raven from Piaget's writings, the child acquires the concept of momentum followed in order by conservation of matter, proportional use of mass and speed with momentum held constant and finally the concept of speed. According to the learning hierarchy derived by logical analysis by Raven the expected order of acquisition is conservation of matter, speed, proportional use of mass and speed with momentum held constant, and finally acquisition of the concept of momentum. The appropriateness of these two alternative hierarchies was tested on 160 children selected randomly. They were individually administered a set of six tasks representing the concepts involved in the hierarchies. The order of administration of the tasks was randomized. The tasks were compared according to their level of observed difficulty. The results favored acquisition of the concepts involved in the order represented by the developmental hierarchy.

Griffiths (1979) argues that this interpretation may be less certain than the author suggests for several reasons. First, only one task was used to test each concept, with the exception of the concept of momentum where two tasks were used. Second, the task testing understanding of speed was perceptually different to the other tasks in that the subjects could not directly observe the objects whose speed was being compared. More importantly, Griffiths indicates that the hypothesized learning hierarchy may not be a learning hierarchy at all, because it appears that this hierarchy was derived by re-combining the components of the developmental hierarchy in a "logical" order. Further he suggests that the steps involved in the hierarchy are very large, and a more precisely defined hierarchy may yield different results. Finally, Griffiths notes that in Raven's study understanding of the concept of momentum is considered only to an intuitive level. This is in opposition to that required for a learning hierarchy where mastery of the component skills is required if further progress is to be made through the hierarchy. Based on the above objections, Griffiths concludes that it is not surprising that a logical hierarchy was not substantiated by the data.

Murray (1981), expressing opinions similar to those of Griffiths (1979) above, also indicates that Raven's (1968) logical hierarchy was inadequately developed. Hence, he argues that it cannot allow a meaningful conclusion, either with respect to the specific concept or to the relationship between psychological and logical hierarchies in general. Therefore, Murray further investigated Raven's claim using the psychological hierarchy developed by Raven and, because of his belief that Raven's logical hierarchy was inadequately constructed, an alternative logical hierarchy hypothesized by Murray.

Using two test items for each element in the hierarchies, Murray collected data by the group-testing of 197 subjects from grades one to eight. The test of inclusion and the ordering-theoretic method were used to analyze the data and arrive at a hierarchy which was considered to represent a psychometrically valid hierarchy. Murray indicates that the results of this analysis do not support Raven's contention that young children develop an understanding of the concept momentum in accordance with a psychologically derived hierarchy, rather than a logical hierarchy. Instead, with little change, the logical hierarchy hypothesized by Murray was substantiated.

A study which shows much support for the cumulative learning model was reported by Wiegand (1969). Wiegand focused upon a logical analysis of a variation of Piaget's inclined plane task (Inhelder & Piaget, 1958), which involved deriving the relationship between the height and weight of a car on an inclined plane, the weight of a block, and the distance it was pushed when struck by the car. This task was analyzed to provide a hypothesized hierarchy of intellectual skills, which was then subjected to empirical test. Piaget's inclined plane task served as a test of transfer. The study was designed to test whether the performance of Piaget's final task could be accounted for on the basis of a cumulative learning model. Thirty students (14 boys and 16 girls) who failed a pretest for the final task and also the transfer task, participated in the study. Subjects were assigned to one of three treatment groups representing demonstration-test-retest, test-retest, and test, respectively.

Wiegand found that children who could not perform either the final task or the transfer task did so quite readily when they were taught the subordinate capabilities between the first and second presentation of both tasks. The demonstration had no significant effect on the performance and the initial test did not enable subjects to perform either the final or transfer task except when they had already attained the needed subskills as revealed by their performance on the test. The retest of subordinate capabilities failed in the initial test appeared sufficient to enable subjects to acquire the hypothesized subordinate skills.

Carroll (1973) suggests that Wiegand's study demonstrates the effectiveness of immediate experience of component skills rather than that learning of these skills is prerequisite to learning the superordinate task. This suggestion seems unwarranted when it is noted that in the test group only three out of ten subjects were able to respond correctly to the final task and transfer task in the posttest, yet each of these subjects passed the initial test for the skill immediately subordinate to the final task. Instead, Wiegand's interpretation that the results of this study are indicative of the fact that the development of intellectual skills occurs through the cumulative effect of learning subordinate capabilities rather than by adoption of structures of intellectual growth is favored. Hence the data support the Gagnéan model of learning rather than the Piagetian model of learning.

Bass and Montague (1972) applied Piaget's findings to the construction of learning hierarchies and instructional material for the problem of equilibrium of a cart on an inclined plane. The results support the learning hierarchy for the first task but not for the inclined plane, in each case with the same sample of ninth grade students. Bass and Montague felt that this study helped to substantiate their beliefs that curriculum developers need studies of the fine structure of developmental sequences to supplement Piaget's analysis, and that Gagné-type task analysis procedures could profitably be used in conjunction with Piaget's developmental sequences in the construction of learning hierarchies.

A study reported by Griffiths (1979) had, as one of its three stated purposes, an investigation of the importance of the availability of subordinate skills within a validated hierarchy on the mole concept relative to the importance of learner developmental level to the acquisition of superordinate skills. An extensive discussion on the identification and validation of the hierarchy will be given in the next section. Two tests were designed to elicit information about the prevailing stage of intellectual development of each of the 269 grade ten students used in the study. The first was a "Test of Developmental Level" which consisted of three neo-Piagetian tasks. The second was the Skemp test (Skemp, 1960) of reflective thinking. Griffiths reports that learner developmental level was found to exhibit only moderate correlations with achievement scores for the intellectual skills comprising the validated hierarchy. In all cases the availability of subordinate intellectual skills accounted for much more of the variance of scores on tests of related superordinate skills than did the developmental level test scores. Griffiths interprets this to mean that the availability of specific intellectual skills is more important than the developmental level of the learner to his learning of the mole concept.

The studies cited in this sub-section appear generally to favor the learning hierarchy model, although no definite conclusions may be reached from such a small number of studies.

Studies concerned to identify learning hierarchies. Most learning hierarchies validated to date have been in the areas of science and mathematics. Gagné's own hierarchies contained arithmetic, algebraic and geometric skills. Of the few well known learning hierarchies which exist in science perhaps the best known is "Science--A Process Approach" (SAPA). This K-6 general science program, developed by the American Association for the Advancement of Science, represents the most extreme attempt to apply Gagné's hierarchical model. This program resulted in the integration of hundreds of science skills which the learner was expected to possess at the end of grade six. However, Gagné (1973) suggests that the SAPA hierarchy is not a learning hierarchy at all, because it is too extensive to allow adequate validation.

Most of the reported learning hierarchies relating to science instruction have been concerned with concepts in chemistry. These will be reviewed below along with a study reported by Beeson (1977) dealing with hierarchical learning in electrical science.

An early hierarchy was developed by DeRose (1969) using the "Chemical Bond Approach" (CBA) materials. The hierarchy of 86 basic and 82 optional objectives was not validated.

Boblick (1971) indicated development of a hierarchy leading to the writing of chemical formulae as its terminal skill. No mention was made of its validation.

An investigation which considered the same concept as the present study was reported by Ozsogomoyan (1979). The main purpose of the study was the design and development of an individualized instruction package intended to teach some major concepts of stoichiometry to unprepared students enrolled in a first-year college chemistry course. Instructional materials were produced following a Gagnéan-type task analysis, which resulted in a detailed hierarchy of intellectual skills. The superordinate skill was the ability to calculate the yield of a product in a limiting-reagent problem. No mention was made about whether the hierarchy was validated or not, although the instructional materials appear quite successful.

Seddon (1974) employed a self-instructional booklet concerned with the development of students' understanding of the "Kimball Charge Cloud Model" of chemical bonding. The sample consisted of 641 students, of whom 533 were preparing for "O" and "A" level chemistry examinations while the remaining 108 were enrolled in first year university or teacher training college chemistry courses. A pretest, which was also used as a posttest at the end of instruction, based on the content of the unit was administered to the students before they commenced the unit. It was hoped to determine the relative effectiveness of the pretest, a general chemistry test administered before commencement of the study, intelligence as measured by a general intelligence test and age as predictors of achievement on the posttest. Seddon interpreted the results of a regression analysis, which indicated that general chemistry knowledge was the best predictor followed closely by the pretest, as supporting Gagné's hierarchical model. Griffiths (1979) disagrees with this interpretation because the general chemistry test was not concerned with capabilities specifically prerequisite to skills tested in the posttest.

In a well executed study by Okey and Gagné (1970), a programmed unit on solubility product calculations was developed. The program included instruction on 16 subordinate skills derived by a Gagné-type task analysis. Four different tests were used to measure student performance: a pretest and posttest on the criterion task and a pretest and posttest on the subordinate skills in the learning hierarchy. The equivalence of these tests was determined in a separate investigation by submitting pairs of items to students. Items meeting the criterion of 80% pass or fail on both questions were selected for the final form of the tests. The sample consisted of 135 tenth, eleventh, and twelfth grade chemistry students in five chemistry classes. Two equal groups were randomly selected from each class. Approximately seven class periods of 50 minutes each were required for a treatment group to take the test and complete the learning program. The first group completed the unit while the second group was involved in an unrelated chemistry unit. The second group then completed the revised unit. A significant difference in the level of performance was confirmed for the second group as compared to the first. The researchers thus concluded, in accordance with the cumulative learning model, that adding instruction leading to improved performance on subordinate skills in a science learning task significantly improved performance on the criterion task.

Despite the attractiveness of the study, Griffiths (1979) notes that the skills involved were not defined as precisely as they might have been. In some cases one subordinate skill such as "solve solubility product problems" might encompass a wide range of outcomes.

Griffiths further criticizes the study for the fact that the percentage of individuals successful on subordinate skills was less than desirable. For example, for each of nine out of fifteen subordinate skills, less than 80% of the experimental group were successful. For four of these skills less than 40% were successful. Griffiths argues that the lack of these subordinate skills for individual subjects was not investigated, nor were specific transfer effects between skills. As a result, the validity of the hierarchy in terms of both its psychometric and transfer characteristics may be less encouraging than the results imply.

A study relating to the identification of a hierarchy concerning the mole concept is reported by Gower, Daniels and Lloyd (1977a). It is an extension of an earlier study (Gower, Daniels & Lloyd, 1977b) which identified a series of underlying concepts which the authors felt were necessary for an understanding of the processes used in the solutions of problems involving the mole concept. The authors commented that their initial theoretical analysis indicated two independent hierarchies, one consisting of concepts based on empirical experience and the other representing a hierarchy of theoretical concepts. Data for the analysis were obtained by requiring the sample (N=42) to respond to a set of items representing the elements of the hypothesized hierarchies. The results of the top 27% and the bottom 27% of the sample were used for analysis. Each element in the hierarchy was tested by four items representing recall, comprehension, application and analysis, respectively. The possibility of a hierarchical relationship between each element and each of those hypothesized to be subordinate or equivalent to it was tested by applying a consistency ratio. An arbitrary value of 0.85 for the consistency ratio was considered acceptable evidence for the existence of a hierarchical connection between two skills. Although the authors claim that their results support the hierarchical model, examination of their data suggests otherwise. The empirical hierarchy shows only 12 out of 18 connections in its "validated" hierarchy having a consistency ratio of 0.85 or more, while the "validated" hierarchy for the theoretical hierarchy shows only seven out of 22 connections achieving the critical value for the consistency ratio. It appears that the results of the study deny rather than support the existence of a hierarchy leading to the mole concept. Griffiths (1979) indicates that the study does not allow any firm conclusions to be made. He comments that the consistency ratio is not an appropriate measure of hierarchical dependency as it is similar in nature to the indices of Gagné and Walbesser, the serious shortcomings of which have already been described. In addition, the authors appear to misunderstand the meanings of the term intellectual skill as defined by Gagné.

In a recent study, Anamuah-Mensah (1981) made use of the Gower, Daniels and Lloyd hierarchy. The influence of structure (using the proportional reasoning schema in Piaget's theory of intellectual development) and content (using Gagné's cumulative learning theory) on the performance of chemistry students on volumetric analysis problems was investigated. An integrated path analytic model was used to analyze the data.

Anamuah-Mensah postulated that Piaget's direct and inverse proportionality constitute the formal structures underlying volumetric analysis calculations. Further, he hypothesized that inverse proportionality underlies the subsumed prerequisite concepts necessary for volumetric calculations and that a knowledge of these subsumed prerequisite concepts is required for successful performance on these calculations. Therefore, his postulated integrated model has direct proportionality as a variable determined by causes outside the model, while inverse proportionality, subsumed concepts and volumetric analysis calculations are variables determined by causes within the model.

Path analysis of data from 256 grade twelve subjects upheld the validity of the integrated model in explaining subjects' performance on volumetric analysis calculations. Anamuah-Mensah inferred this to mean that direct proportional reasoning has a direct influence on inverse proportional reasoning and that acquisition of direct proportional reasoning precedes acquisition of inverse proportional reasoning. Further, he suggested that the results show that inverse proportional reasoning has a direct influence on knowledge of subsumed prerequisite concepts, which in turn has a substantial direct influence on performance on volumetric analysis calculations. He therefore concluded that direct proportional reasoning influences subsumed concepts mainly through inverse proportional reasoning while inverse proportional reasoning influences performance on volumetric analysis calculations mainly through the knowledge of subsumed prerequisite concepts.

Despite the author's claim to have applied Gagnéan theory in his study, Anamuah-Mensah's hierarchy appears to represent relationships more general than those required in a learning hierarchy. Further, the use of path analysis seems to reflect only transfer and not psychometric relationships.

A study by Griffiths (1979), previously mentioned in the last section, had as another purpose the identification of a hierarchy for the mole concept. This will be described in some detail because the present study is patterned directly upon it. The hypothesized hierarchy was derived using the first five of the nine steps suggested by White (1974b). This resulted in a hypothesized hierarchy of eight skills, with the ability to relate masses of chemical substances in terms of the relative number of particles present as the superordinate skills.

The sample consisted of 269 grade-ten students, of whom 133 were boys and 136 girls. The instruments used in the identification of the hierarchy consisted of three chemistry quizzes, a final chemistry test, and two remedial units. Each element in the hypothesized hierarchy was represented on the test and quizzes by a number of questions. In no case was the number any less than two. The remedial units contained further instruction and test questions representing selected intellectual skills from the hypothesized hierarchy.

The sample was randomly divided into two subgroups, one of which was designated remedial, and the other non-remedial. The remedial group was required to complete the two remedial units as take-home assignments between testing of skills involved and instruction of the next skill.

The experimental procedure for testing differed substantially from that recommended by White in steps six and seven. The students in both groups were instructed by their respective teachers rather than using a programmed format. Class quizzes, testing the skills taught immediately previously, were constructed by the researcher and administered by the classroom teachers at appropriate times. Each quiz was marked immediately by the classroom teacher. The results of the quiz, together with a remedial unit representing the skills just taught, were given to the students at that time. Several days after the last instructional period both groups received a final chemistry test, which covered all of the items in the hierarchy. The items used on the final chemistry test were parallel to those used on the three quizzes. This procedure is in contrast to White's recommendation of programmed instruction and testing only during instruction.

The validation procedure also differed substantially from that recommended by White in steps eight and nine. In addition to the White and Clark (1973) test of inclusion, the ordering-theoretic method and the Dayton and Macready method were applied to the data. Further, transfer of learning was investigated by comparing performance on superordinate skills in the Final Test for subjects who had gained related subordinate skills between quizzes and the Final Test. This is in contrast to White who recommends the use of the test of inclusion and no test of transfer.

Griffiths reports that the hypothesized hierarchy was not substantiated by any of the tests applied, but the data suggested alternative hierarchies. The extensiveness and structure of these hierarchies varied according to the degree of stringency applied to the statistical tests. Application of the ordering-theoretic method and the White and Clark test to the same data yielded good agreement. Application of the Dayton and Macready method to the same data yielded a basically similar hierarchy, and allowed direct comparison of alternative hierarchies which had been found difficult to distinguish by application of the test of inclusion and the ordering-theoretic method.

Griffiths concluded that a learning hierarchy for the mole concept had been identified and validated both in terms of the psychometric and learning transfer relationships between the component skills. The hierarchy contained seven of the eight skills originally hypothesized.

Beeson (1977) reported a study which investigated the application of the idea of learning hierarchies to electrical science. The final task in the hierarchy concerned itself with the determination of quantities in electric circuits. This study incorporated White's (1974b) model for hierarchy validation in a modified form. White recommended the use of a suitable test of hierarchical relationship which allowed for errors of measurement only. Beeson modified this so that one could use three different null hypotheses representing three different levels of rigor for testing the validity of the connections between elements.

After constructing the hierarchy by a Gagnéan-type task analysis, and writing two questions for each element in the hierarchy as well as a learning program, the materials were piloted on tenth-grade students. This resulted in modifications being made to the hierarchy, test questions and learning program. The final form of the learning program was given to five classes of tenth-grade students, representing a total population of 166 students.

Although White recommended that no exceptions to any postulated hierarchical connection be allowed except those arising from errors of measurement, Beeson suggested that this would eliminate hierarchical connections which are valid for the great majority of the students. To account for this possibility he tested the validity of the connections in the hypothesized hierarchy at three levels designated

00, 01, and 05, in which it was hypothesized that 0%, 1%, and 5%, respectively, of students achieving the higher element would be able to do so without having learned the lower element. Using these three levels, Beeson found that 21 of the 34 connections between pairs of intellectual skills were valid at the most rigorous (00) level, and six more were valid at one of the two weaker levels. Also, Beeson reported that in cases where verbal information was used as an element instead of an intellectual skill, no cases were found in which connections leading up to verbal information elements were accepted as valid at the most rigorous level, and in only one case was such a connection accepted at the weaker (05) level. In all other cases verbal information elements included in the hierarchy were found to be subordinate to intellectual skills.

Beeson concluded that the study had validated a learning hierarchy in electrical science, provided further evidence for the distinction between intellectual skills and verbal information units in learning hierarchies, demonstrated the use of the application of the learning hierarchy idea to an area involving some non-mathematical learning, and developed a rigorous validation procedure which leads to further clarification of the learning hierarchy concept, and of the acceptable component elements of hierarchies.

Summary

A description and discussion of the most important techniques which have been used to identify and validate learning hierarchies has been given. A review of the literature relating to learning hierarchies in science, and chemistry in particular, was presented. In general, it may be tentatively concluded that the learning hierarchy model appears to be important. However, the results of many particular studies in which an attempt has been made to identify learning hierarchies must be considered equivocal.

Particular details of the methods used in the present study follow from a consideration of the studies reviewed in this chapter. These details are amplified in chapter three.

CHAPTER 3

DESIGN, INSTRUMENTATION AND PROCEDURES

A number of steps are involved in the identification of a learning hierarchy. These include generation of a hypothesized hierarchy, development of suitable test questions for each element of the hierarchy, design and implementation of appropriate instructional and testing procedures, use of these procedures with a selected sample, and analysis of the results. This chapter describes each of the foregoing steps as applied in the present study together with the rationale for each decision made.

Construction of the Hierarchy

The superordinate skill for the hierarchy hypothesized in this study, chosen for the reasons discussed in chapter one, was the ability, when given a balanced chemical equation and the masses of two reactants, one of which is in excess, to calculate the mass of a designated product. The hypothesized hierarchy was derived by asking the question, "What should the learner be able to do if he is to learn this skill?" first of the terminal skill and then for each successive skill. This process continued until a skill was reached which could not reasonably be broken down further. This procedure resulted in the identification of nine skills being arranged hierarchically.

As advocated by White (1974b), the reasonableness of the hypothesized hierarchy was checked with subject-matter experts. After extensive discussion with three science educators a revised hypothesized hierarchy was produced. This is represented in Figure 6. Changes were made in the skills represented in the hierarchy, their wording and their order.

At this point four items for each skill in the hierarchy were written by the author. In doing so, a number of things were kept in mind. First, all items for each skill had to have an equal level of difficulty and second, any numerical competence required in an item for a skill was kept to a minimum. It was hoped that doing so would avoid confounding conceptual relationships by mathematical difficulties.

Analysis of Skills 5 and 7 indicated that these skills could be tested using a minimum of four questions per skill, each of which tested a different aspect of the skills. The conventional item for these skills would give the mass or number of moles of a reactant and require that the mass or number of moles of a product be calculated ($R \rightarrow P$). A second item would give the mass or number of moles of one reactant and require that the mass or number of moles of another reactant be calculated ($R \rightarrow R$). A third item, which requires the student to work in the opposite direction to that required for the more common and conventional $R \rightarrow P$ item, would give the mass or number of moles of a product and require that the mass or number of moles of a reactant be calculated ($P \rightarrow R$). A fourth item would give the mass or number of moles of one product and require that the mass or number of moles of another product be calculated ($P \rightarrow P$). It was decided to test for each of the four aspects, when writing items for Skills 5 and 7.

Once the items were devised, the panel of science educators checked their appropriateness. Except for some minor wording changes,

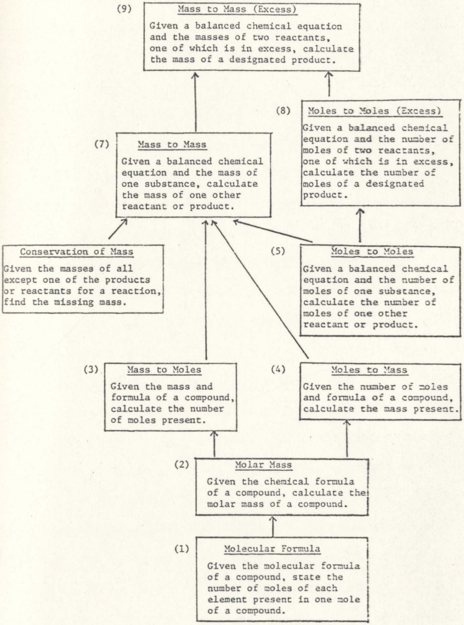


Figure 6. The hypothesized hierarchy.

most of the items were left intact. In all, 36 items were written. These items were used to make up two parallel tests containing 18 items which represented two items for each skill in the hypothesized hierarchy. The skills were scrambled on each test to prevent bias in favor of or against the hierarchy. The tests were used in a pilot which is described below.

Using the hypothesized hierarchy and the items devised for each skill, an individual instructional booklet was produced by the author. Each skill in the hypothesized hierarchy was covered, and at the end of a section for each skill a number of suitable exercises were assigned. The answer to each exercise was provided. The exercises were parallel to the items devised for each of the skills earlier.

Again, the panel of science educators reviewed the instructional booklet. Some minor format changes were recommended. The content was left intact.

The tests and instructional booklets were then piloted. Although it would have been desirable to use a grade ten class in a senior high school, it was impossible to gain access into one. As an alternative, students enrolled in the first semester of an introductory chemistry course at Memorial University were used. Two classes of first-year students (N=48), who had no previous background in chemistry were used. Both classes were taught by the same professor and had just recently completed their treatment of the mole concept. Prior to testing, the professor and students were told they would be asked to comment on the materials.

Each class was required to do one of the two parallel tests of 18 items each during a single 50-minute setting. Following this, the results of the chemistry test and an instructional booklet were given to each student. They were asked to complete it and make a note of any comments they had as they worked through it.

The results of the field test proved to be invaluable. First, it was decided that four questions per skill, although very desirable, would be impractical to test in the time period provided for testing. Most of the university students were just able to complete the 18-item tests during a 50-minute period. In a school situation with only a 45-minute period at the most, of which 5 minutes would be lost for administrative purposes, most students would not be able to complete the 36 items which would be on each test. Therefore it was decided to restrict the number of items per skill to two, which resulted in equivalent 18-item test.

Second, the wording in some items had to be changed, so as to make what was required of the student clearer. For example, an item for Skill 1 originally read "The molecular formula for barium bromide is $BaBr_2$. How many moles of each element are contained in one mole of barium bromide?" After being reworded the question read, "How many moles of barium (Ba) and bromine (Br) are contained in one mole of barium bromide ($BaBr_2$)?"

Third, the decision to go with two instead of four questions per skill resulted in only one of the four possible aspects of Skills 5 and 7 being tested. It was decided to use only those items which tested the conventional aspect of reactant to produce ($R \rightarrow P$). Although it was felt that similar skills were used in the other three aspects (($R \rightarrow R$), ($P \rightarrow R$), ($P \rightarrow P$)), it seemed possible that the items representing these might be sufficiently different than the conventional aspect ($R \rightarrow P$), to confound the result for this skill and hence affect the validity of the hierarchy.

Fourth, some equations for one or other of the two items per skill were more difficult to work with than others. Thus, more consistent equations were used so that items testing the same skills would be at the same level of difficulty.

Fifth, a problem was found with the items for Skills 8 and 9, the "excess" skills. Some subjects appeared to be choosing the first reactant in the given equation automatically as the limiting reagent each time. In items where the limiting reagent was the second reactant in an equation they would automatically get the item incorrect, even though they used the correct sequence of steps to solve the problem. To avoid this, the limiting reagent in the items for Skills 8 and 9 was now always the first reactant in the equation. However, because it was of interest to investigate the errors arising from placing the limiting reagent as the second reactant in an equation, two additional items were added to each test which consisted of one item each for Skills 8 and 9. In these items the limiting reagent is the second reactant in each case. These two extra items were placed at the end of each test. Students were required to attempt them only after having done the required items for the hypothesized hierarchy.

The contents of the instructional booklet were left intact. Hence, following the pilot study two parallel tests of 20 items each and an instructional booklet were considered acceptable for use in the study. The modifications of the questions resulted in no changes to the hypothesized hierarchy shown in Figure 6. The wording and sequencing of the nine skills remained the same. A description and illustrative example of each of the skills is given in the next section.

The Skills in the Hypothesized Hierarchy

Skill 9. *Given a balanced chemical equation and the masses of two reactants, one of which is in excess, calculate the mass of a designated product.*

For example, "Consider the reaction between calcium fluoride (CaF_2) and hydrogen chloride (HCl) according to the equation:

$$CaF_2 + 2HCl \rightarrow CaCl_2 + 2HF$$

If 39 grams of CaF_2 and 73 grams of HCl are mixed together and allowed to react until no further reaction occurs, calculate the mass of hydrogen fluoride (HF) produced."

Skill 8. *Given a balanced chemical equation and the number of moles of two reactants, one of which is in excess, calculate the number of moles of a designated product.*

For example, "Consider the reaction between hydrogen gas (H_2) and chromium chloride ($CrCl_3$) according to the equation:

$$3H_2 + 2CrCl_3 \rightarrow 2Cr + 6\ HCl$$

If 4 moles of H_2 and 4 moles of $CrCl_3$ are mixed together and allowed to react until no further reaction occurs, calculate the number of moles of hydrogen chloride (HCl) produced."

Skill 7. *Given a balanced chemical equation and the mass of one substance, calculate the mass of one other designated reactant or product.*

For example, "Ethane (C_2H_6) reacts with oxygen gas (O_2) according to the equation:

$$2C_2H_6 + 7O_2 \rightarrow 4CO_2 + 6H_2O$$

Calculate the mass of carbon dioxide (CO_2) produced by 15 grams of ethane."

Skill 6. *Given the masses of all except one of the products or reactants for a reaction, find the missing mass.*

For example, "Calcium (Ca) combines with sulfur (S) to produce calcium sulfide (CaS) according to the equation:

$$Ca + S \rightarrow CaS$$

What mass of CaS would be produced if 4 grams of Ca and 3.2 grams of S reacted?

Skill 5. *Given a balanced chemical equation and the number of moles of one substance, calculate the number of moles of one other designated reactant or product.*

For example, "Iron oxide (Fe_2O_3) reacts with carbon (C) according to the equation:

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$$

Calculate the number of moles of iron (Fe) produced by 6 moles of iron oxide."

Skill 4. *Given the number of moles and formula of a compound, calculate the mass present.*

For example, "Calculate the mass of carbon dioxide (CO_2) in 2.0 moles of carbon dioxide.

Skill 3. *Given the mass and formula of a compound, calculate the number of moles present.*

For example, "Calculate the number of moles of sodium oxide (Na_2O) in 124 grams of sodium oxide."

Skill 2. *Given the chemical formula of a compound, calculate the molar mass of the compound.*

For example, "Calculate the molar mass of water (H_2O)."

Skill 1. *Given the molecular formula of a compound, state the number of moles of each element present in one mole of the compound.*

For example, "The molecular formula of iron oxide is Fe_2O_3. How many moles of iron (Fe) and oxygen (O) are contained in one mole of iron oxide?"

Although one may argue that the hypothesized hierarchy is not very large, it was felt that given the amount of time available in the schools being used in the study, it could not be any larger. The content in the present study involved the use of four periods for administering the tests, and another double period to complete the developmental aspect of the study which was mentioned in chapter one. Also, as indicated in chapter one, Gagné (1974) has suggested that the content of a learning hierarchy should be restricted to one lesson. The hypothesized hierarchy exceeds this criterion somewhat. Thus it was concluded that the hypothesized hierarchy was of a sufficiently large size for adequate study.

Experimental Design

The actual design used in this study is illustrated in Figure 7. In addition to being concerned with the identification of a learning hierarchy relating to stoichiometry, the present study, as indicated earlier, is part of a larger study (Griffiths, 1980), concerned with identifying the relationship between learner developmental level and acquisition of the skills which compose the hierarchy. The placement of the developmental level testing, which was done in conjunction with the hierarchy testing, is therefore included in Figure 7.

Sample

The sample consisted of 180 grade ten students enrolled in introductory chemistry courses in three senior high schools in St. John's. There were 85 boys and 95 girls. Five classes and three teachers were involved. Each of the schools was using a different chemistry text. One class in two of the schools was piloting a new chemistry program for grade ten. The intake of the schools represents a wide socioeconomic background and appears to be quite representative of North American urban areas.

Procedure

The teachers involved in the present study were asked not to depart from their usual mode of instruction, and to follow a course of

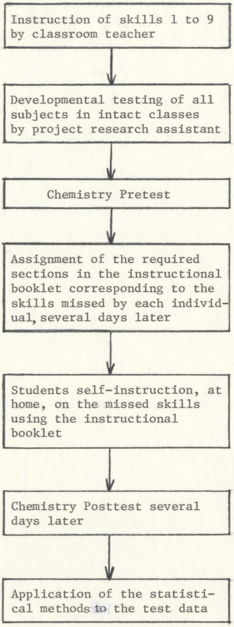


Figure 7. Design of experimental procedures.

study based upon the particular text they were using. In two of the schools instructional practice is characterized as conventional, involving teacher exposition accompanied by student laboratory activities. In the third school the instructional practice involved, for the most part, only teacher exposition.

The teachers involved in the study first taught the contents of the hierarchy to their respective classes. This required a time period of several weeks.

A few days after instruction relating to the contents of the hierarchy ended, the developmental level testing was conducted by the project research assistant. This entailed the use of one double-period setting.

Several days after the developmental testing ended, the students were administered the Chemistry Pretest by the investigator. It should be noted that the pretest was preliminary to individual remediation, not to general instruction, and that the investigator is a qualified teacher of several years standing. In two of the schools the pretest was administered in a one double-period setting, while in the other school it was necessary to use two single periods. This necessitated splitting the pretest of 20 questions into two parallel parts, each containing one test item for each skill in the hypothesized hierarchy. In each part the questions were randomly assigned. Part one was always administered first. The first school to be tested was the one which provided the single period settings, therefore requiring the use of parts one and two of the pretest respectively. To be consistent it was decided to keep the pretest as two separate parts in the remaining two schools, even though they both provided a double-period setting. Students in these schools were given part one first and, when they were ready, part two. Both parts were collected together at the end of the double period.

In only one class was sufficient time not available for all subjects to complete the test. This was in the school requiring a single period to administer part one of the pretest. Some students were not able to finish the last two questions on the test, the last of which was the additional item testing Skill 9, which had the limiting-reagent as the second reactant in the equation, and therefore was not representative of skills in the hierarchy. In all cases, it and the other unanswered question were treated as missing data. In all other cases using only one or both parts of the pretest, sufficient time was available for students to complete the test.

The procedure used to test the existence of psychometric hierarchical relationships between the hypothesized skills were described in chapter two. In addition to these tests, a test for transfer of learning was incorporated into the design. The essence and method of application of this test will now be described.

In order to determine the existence and strength of transfer of learning from the subordinate skills in the hypothesized hierarchy to the related superordinate skills, the students were assigned instructional booklets and requested to complete the individually indicated sections. These sections corresponded to those skills in the hierarchy on which the individual was weak as evidenced by the results in the Chemistry Pretest. Any subject obtaining an incorrect answer for one or both of the items which represented a particular skill was required to complete the section for that skill. The instructional booklets were given to the students several days after the pretest.

They were told when the investigator would be returning to retest them, which in all cases was three or four days after the booklets were given out, and asked to have the relevant material covered by then. Every student, regardless of his or her results, received a booklet. Some subjects had to cover all of the skills, but for most subjects only two or three skills required remediation. The students did not have to return the booklets. At the end of this time the investigator administered the Chemistry Posttest, a parallel form of the pretest. It was to be used to see if the students could now exhibit those skills which they had initially failed to demonstrate. In particular, these data were used to test for transfer of learning from subordinate to superordinate skills. The essence of this test (Griffiths, 1979) is to investigate the relationship of gain of subordinate skills between the Chemistry Pretest and Chemistry Posttest and gain of related superordinate skills in the Chemistry Posttest. The following steps were involved in this part of the analysis:

1. Those skills in the hypothesized hierarchy which are directly subordinate to any other skills in the hierarchy were identified.
2. Subjects who failed to exhibit any of these subordinate skills in the Chemistry Pretest were identified for each particular skill and for a group of these skills where a group was directly subordinate to any particular skill(s) in the hypothesized hierarchy. The size of the sub-sample in this way varies from skill to skill.
3. The performance in the Chemistry Posttest of the subjects identified in step 2 was determined with respect to whether or not the subject exhibited the subordinate skill(s) he failed to exhibit in the Chemistry Pretest. These subjects were

labelled "Gain" if they exhibited the skill(s) in the Chemistry Posttest and "No Gain" if they failed to exhibit the skill(s) in the Chemistry Posttest.

4. The performance on the Chemistry Posttest of each of the subjects identified in step 2 was determined with respect to any skill superordinate to any of the subordinate skills he failed to exhibit in the pretest. Based upon performance on this superordinate skill, subjects were designated as "Pass" or "Fail" for the particular skill.
5. The significance of the relationship between Gain/No Gain and Pass/Fail was determined by application of a chi-square test, with one degree of freedom in each case.

The Chemistry Posttest was administered in two of the schools in a double-period setting, and in the third school in two single-period settings. Test design and administration were identical to the procedures for the pretest.

The chemistry tests are described in the section which follows. Parts one and two of the Chemistry Pretest are represented in Appendices 1 and 2, respectively, while parts one and two of the Chemistry Posttest are represented in Appendices 4 and 5. The relationship between item numbers and skills tested is given in Appendix 3 for the pretest and in Appendix 6 for the posttest. The instructional booklet is duplicated in Appendix 7.

Instruments

Two tests were administered during the course of the study, namely the Chemistry Pretest and the Chemistry Posttest. During the course of the study it was necessary to split both tests into two parts. Each part is presented in detail in Appendices 1, 2, 4 and 5.

Each skill in the hierarchy is represented by two questions in each test. The order of questioning is scrambled to prevent bias in favor of the hierarchy. Two additional items, consisting of one question each for Skills 8 and 9, were added to both tests in order to test the ability of students to correctly exhibit these skills when the limiting reagent is given as the second reagent in the chemical equation provided in the items. These items were not included in the statistical analyses.

For the reasons discussed earlier, the Chemistry Pretest and Posttest each had to be divided into two parallel parts, both of which contained ten questions. These were named "Part One" and "Part Two." Each skill of the hierarchy is represented by one question in each part. The order of questions is scrambled to prevent bias in favor of the hierarchy. An additional item representing Skill 9 is found in each part one, and an additional item representing Skill 8 on each part two. Each additional item is the last item on each part of the pretest. Students were required to attempt these only after completing the nine items for the hypothesized hierarchy, and if time permitted.

Summary

A description of the procedure used to identify and construct the hypothesized hierarchy has been given. This resulted in the identification of a hypothesized hierarchy containing nine skills leading to the ability to "calculate the mass of a designated product when given a balanced chemical equation, and the masses of two reactants, one of which is in excess." For each skill, an illustrative example of an item used to test that skill was given. Experimental design was outlined, and the sample and procedures which were used were described. The chapter concluded with a brief description of the instruments used in the study.

The design, instruments and procedures described in this chapter led to the collection of data which were used to test the validity of the hypothesized hierarchy. Analysis of these data forms the focus of the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

Introduction

Each of the tests used in this study is essentially composed of a number of two-item tests, with one such test for each skill. The basic data used to test the validity of the hypothesized hierarchy are derived from the responses of individuals to these tests. Therefore, the validity and reliability of each test is of much importance. This chapter begins with a discussion of the validity and reliability of the tests, followed by the results of applying the White and Clark (1973) test of inclusion, the ordering-theoretic method (Bart & Krus, 1973; Airasian & Bart, 1975) and the Dayton and Macready (1976) scaling method to the data from the tests. Collectively, these analyses allow for a judgement of the validity of the hypothesized hierarchy and possible modifications of it. Following these analyses a "preferred" psychometrically validated hierarchy is suggested which is then further tested by considering the degree of transfer of learning from subordinate skills to related superordinate skills. For the White and Clark test of inclusion a locally written computer program (Cornish, 1978) was used. For the application of the Dayton and Macready method the computer program developed by Dayton and Macready (1976b) was used. All other statistical procedures were performed using the SPSS 300 statistical package (Nie _et al_., 1975).

Validity of the Test Items

To ensure good content and construct validity, as indicated in chapter three,three science educators, of whom two were experienced chemistry teachers, were asked to examine the behavioral statement for each skill in the hypothesized hierarchy and the items testing that skill. Also, as indicated in chapter three, the items testing the skills within the hypothesized hierarchy were piloted with two classes of first year chemistry students who had no prior experience in chemistry. In some cases changes were made to test items, mainly because they were worded inappropriately.

Reliability of the Test Items

The White and Clark test, although not requiring a mastery decision, requires that the items testing a particular skill should exhibit low inter-item variance. As the Chemistry Pretest and Posttest both represent a number of two-item tests, conventional reliability statistics are not meaningful. Consideration was given to using the phi correlation as an index of the degree of correlation between two items testing the same skill. However, the potential for distortion of marginal totals because of the small number of students who got some items incorrect rendered the results of the phi correlation less meaningful. Consequently, the theoretically less pleasing method of reporting percentage agreement was adopted. Ideally, perfect agreement between two items testing the same skill should be obtained. In practice such perfect agreement is seldom found, as individual items representing the same skill may not be identical in structure or presentation. Hence, while perfect agreement could not be expected, substantial percentage agreement was considered necessary between each item testing a particular skill. The values obtained for the Chemistry Pretest are presented in Table 1, and those for the Chemistry Posttest in Table 2. The values in each table indicate the strength of a particular relationship between test items testing the same skill. The value of N varies between tests for several reasons. First, some subjects were absent for a particular testing session. Second, some subjects' responses to a particular item were difficult to interpret and thus were treated as missing data. Finally, a few subjects in one class, as indicated in chapter three, had insufficient time to finish some items on the Chemistry Pretest. In all cases, these items were treated as missing data.

The values of the percentage agreements presented in Tables 1 and 2 indicate good agreement between items testing the same skill. Therefore all items were retained. In the sections which follow the data collected from the use of these items will be used to answer the research questions posed in chapter one.

Tests Applied to the Data

Two psychometric tests which were used in this study consider skills in pairs. These are the White and Clark (1973) test of inclusion and the ordering-theoretic method (Bart & Krus, 1973; Airasian & Bart, 1975). Both were used in this study for a number of reasons. First, some sifting of the data is desirable before the Dayton and Macready (1976) method, the third psychometric test used in this study, is applied. To accomplish this it was necessary to use at least one of the two methods which considers skills in pairs. Second, because the

Table 1

Percentage of Agreement Between Items Testing the Same Skill on the Chemistry Pretest

Skill	Test Items*	Number of Subjects	Percentage Agreement Between Items
1. Molecular Formula	01,01	163	84
2. Molar Mass	07,06	163	95
3. Mass to Moles	04,02	163	95
4. Moles to Mass	02,05	163	94
5. Moles to Moles	05,09	158	91
6. Mass to Mass A	08,08	161	79
7. Mass to Mass B	06,03	163	93
8. Moles to Moles (Excess)	09,07	152	78
9. Mass to Mass (Excess)	03,04	163	76

Note: *In each case the first number in column two represents the item testing the skill on part one of the pretest, while the second number represents the item testing the same skill on part two of the pretest.

Table 2

Percentage of Agreement Between Items Testing the Same Skill on the Chemistry Posttest

Skill	Test Items*	Number of Subjects	Percentage Agreement Between Items
1. Molecular Formula	01,01	165	98
2. Molar Mass	06,07	164	98
3. Mass to Moles	02,04	164	98
4. Moles to Mass	05,02	165	98
5. Moles to Moles	09,05	164	99
6. Mass to Mass A	08,08	164	91
7. Mass to Mass B	04,06	164	93
8. Moles to Moles (Excess)	07,09	161	93
9. Mass to Mass (Excess)	03,03	164	81

Note: *In each case the first number in column two represents the item testing the skill on part one of the posttest, while the second number represents the item testing the same skill on part two of the posttest.

relationship between the White and Clark test and the ordering-theoretic method is of current interest, it was felt that it would be useful to report the degree of congruence between the two methods. Hence, both psychometric methods which consider skills in pairs were used in this study.

The three tests were applied only to the Chemistry Pretest data and not to the Chemistry Posttest data. It was felt that the latter could not be used to psychometrically validate the hypothesized hierarchy, as most students had to complete some section(s) in the Instructional Booklet before doing the Chemistry Posttest. As the Instructional Booklet contained instruction and appropriate exercises designed around the hypothesized hierarchy, it was felt that the use of it may bias the Chemistry Posttest data in favor of the hierarchy. Therefore, only the Chemistry Pretest data were used when applying the above tests.

The White and Clark (1973) test of inclusion was used to determine the existence of hierarchical connections between pairs of intellectual skills in the hypothesized hierarchy allowing for 0, 1 and 2% exceptions in addition to errors of measurement. In accordance with White and Clark, these were designated as 00, 01 and 02 levels of stringency. In all cases a 5% level of significance was used. Although White (1974b) prefers the absolute criterion of no exceptions other than those attributable to errors of measurement, the literature suggests that substantial rather than absolute hierarchical dependency is acceptable in determining the validity of the connections between skills. Linke (1975) suggests a 2% criterion, while Beeson (1977) allows a 5% exception in addition to those representing measurement error. Griffiths (1979) recommends that the level of stringency be relaxed until the point is reached when the number of bi-directional connections increases. This recommendation is used in the present investigation. The test was applied in both directions to all pairs of skills hypothesized to be hierarchically related.

Application of the Ordering-Theoretic Method and the White and Clark Test to the Data from the Chemistry Pretest

Research question one asks, "Does the arrangement of intellectual skills represented in the hypothesized hierarchy represent a learning hierarchy which is valid psychometrically?" If the answer to this question is negative, research question two will be considered. Research question two asks, "Does some other arrangement of some or all of the intellectual skills represented in the hypothesized hierarchy represent a learning hierarchy which is valid psychometrically?"

The results of applying the ordering-theoretic method to the data are presented in Tables 3 and 4. In Table 3 the designation "upper" and "lower" does not reflect any theoretical position. The table contains the percentage of exceptions to the existence of a hierarchical connection for each pair of skills both in the hypothesized direction and in the direction opposite to that hypothesized, in each case. Table 4 contains a summary of all the hierarchical connections identified after application of the ordering-theoretic method to the data. In this table only those connections for the skills hypothesized to be hierarchical or equivalent were considered. The results of the analysis in Table 4 indicate those skills judged to be subordinate to each of the other eight skills, at the three levels of exceptions previously described.

Table 3

Ordering-Theoretic Method: Percentage of Exceptions to

Hierarchical Connections (Chemistry Pretest)

		"upper" skill								
		9	8	7	6	5	4	3	2	1
	9	-	1.3	10.6	12.6	25.2	31.1	34.2	36.6	16.0
	8	2.7	-	11.3		22.4	29.8			
	7	0.6	2.0	-	6.9	12.8	19.8	22.2	25.9	13.0
"lower"	6	0.6	0.7	5.6	-					
skill	5	1.3	0.0	1.3		-				
	4	0.0	0.7	0.0			-	2.5	2.5	0.6
	3	0.0	0.0	0.0			1.2	-	1.9	1.9
	2	0.0	0.0	0.6			0.6	0.6	-	0.6
	1	5.0	5.3	11.1			14.2	21.6	21.0	-

Note: 1) The reader's understanding of this table may be aided by the following explanation. The percentage of exceptions for a particular hierarchical connection may be found by locating the "lower" skill for the connection and then reading directly across from it until the "upper" skill is located immediately above it.

2) A blank indicates that no hierarchical connection was hypothesized for the two skills concerned.

Table 4

Summary of Hierarchical Connections Identified After Application of the Ordering-Theoretic Method to the Chemistry Pretest Data

Level	9	8	7	6	5	4	3	2	1
1%	7	9	5			3	4		4
	6	5	4			2	2		2
	5		3						
	4		2						
	3								
	2								
2%	8	9	5			3	4	3	4
	7	5	4			2	2		3
	6		3						2
	5		2						
	4								
	3								
	2								
5%	8	9	6			3	4	4	4
	7	5	5			2	2	3	3
	6		4						2
	5		3						
	4		2						
	3								
	2								
	1								

Note: The reader's interpretation of the above table may be aided by an illustrative example. Table 4 indicates that Skill 9 is superordinate to Skills 7, 6, 5, 4, 3, 2 at the 1% level to Skills 8, 7, 6, 5, 4, 3, 2 at the 2% level and to Skills 8, 7, 6, 5, 4, 3, 2, 1 at the 5% level.

The results of applying the White and Clark test to the data are represented in Table 5. As in the case of the ordering-theoretic method, only those connections for the skills hypothesized to be hierarchical or equivalent were considered.

With the exception of several connections involving Skill 1, the results obtained from applying the White and Clark test at the 00, 01 and 02 levels, respectively, are similar to those from application of the ordering-theoretic method at the 1, 2 and 5% levels of exception, respectively.

Clearly, slightly different hierarchies would emerge from analysis of the data at different levels of stringency. This poses the question of which hierarchy is more appropriate. Griffiths (1979) argues that although it would seem that the more stringent the test, the more certain one can be of the validity of the hierarchy, the hierarchy established at the less stringent level may be the most informative, provided all skills are of use in their own right as well as in the overall hierarchy. At too strict a level, the hierarchy may become too small to be of practical use. Griffiths further argues that, in the absence of any set criteria, the optimum stringency level may be that at which the number of uni-directional connections begins to decrease. This occurs at the 01 level for the White and Clark test and the 5% level of exception for the ordering-theoretic method.

According to the hypothesized hierarchy all skills should be subordinate to Skill 9 (Mass to Mass (Excess)). The results suggest some anomalies.

First, it was hypothesized that Skill 8 (Moles to Moles (Excess)) was subordinate to Skill 9 (Mass to Mass (Excess)). The results of applying both the ordering-theoretic method and the White and Clark

Table 5

Summary of Hierarchical Connections Identified After

Application of the White and Clark Test to the

Chemistry Pretest Data

Level	9	8	7	6	5	4	3	2	1
00	8	9	6			3	4	4	4
	7	5	5			2	2	3	
	6		4			1			
	5		3						
	4		2						
	3								
	2								
01	8	9	6			3	4	4	4
	7	5	5			2	2	3	3
	6		4			1			2
	5		3						
	4		2						
	3								
	2								
	1								
02	8	9	9			3	4	4	9
	7	5	6			2	2	3	4
	6		5			1			3
	5		4						2
	4		3						
	3		2						
	2								
	1								

Note: The reader's interpretation of the above table may be aided by an illustrative example. Table 5 indicates that Skill 9 is superordinate to Skills 8, 7, 6, 5, 4, 3, 2 at the 00 level and to Skills 8, 7, 6, 5, 4, 3, 2 and 1 at both the 01 and 02 levels.

test to the data suggest that Skill 8 is equivalent to, rather than subordinate to Skill 9. This result will be investigated further through application of the Dayton and Macready procedure, and also in terms of any transfer effect.

Second, the hypothesized connection between Skill 6 (Conservation of Mass) and Skill 7 (Mass to Mass) was not found to exist at all, although a connection was found to exist between Skill 6 and Skill 9. What this result suggests is that the ability to correctly perform stoichiometric calculations does not depend upon understanding that such calculations depend upon the validity of the Law of Conservation of Mass except where an excess of one reactant is involved. However, it may be that such understanding facilitates understanding of, and hence the ability to correctly perform Skill 6-type calculations. Therefore, the strength of a transfer effect from Skill 6 to Skill 7 as well as to Skill 9 will be considered in a later section of this chapter.

Third, instead of Skill 2 (Molar Mass) being subordinate as hypothesized to Skills 3 and 4 (Mass to Moles and Moles to Mass, respectively), the results show that it is equivalent to Skills 3 and 4. Even post hoc, this seems to be an illogical relationship. However, it is suggested that because Skills 2, 3 and 4 were exhibited by almost all subjects, it was not possible to differentiate between the skills.

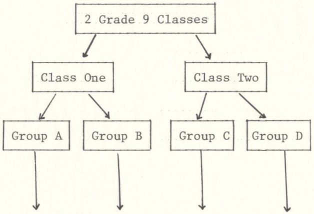
To determine the relationship between these skills an additional sample was taken. This sample was composed of subjects who had no prior exposure to these skills. Two intact classes of grade-nine students (N=57) were involved. Although a larger sample would have been desirable, it was not possible to obtain.

The first of the two classes, Class 1 (N=26), was randomly divided into two groups, Group A (N=12) and Group B (N=14), respectively. Group A received instruction on Skill 2 (Molar Mass) only and was then tested on Skills 2, 3 (Mass to Moles) and 4 (Moles to Mass). Group B received instruction on Skills 3 and 4 only and was then tested on Skills 2, 3 and 4. They were then taught Skill 2 and retested on all these skills.

The second class, Class 2 (N=31), was also randomly divided into two groups, Group C (N=15) and Group D (N=16), respectively. Group C received instruction on Skills 2 and 3 only, and was then tested on Skills 3 and 4. Group D received instruction on Skills 2 and 4 only and was then tested on Skills 3 and 4. The experimental design for this additional testing on Skills 2, 3 and 4 is outlined in Figure 8.

The instructional format used for the additional study differed from that used in the main study in that the subjects were taught by the investigator in a group setting. Instruction entailed explanation of the appropriate skill(s) with use of one or two examples and then having the students work through at least two more examples of the skill(s) on their own. The students were then tested on the appropriate skills as indicated in Figure 8. Each skill was tested with the use of two items. The items used to test the skills were scrambled accordingly on the test papers. Instruction and testing of each group required approximately 45 minutes.

The results of the analysis of these data are presented in Table 6. Several conclusions may be derived from the information presented in this table. All 12 subjects taught Skill 2 only were successful on both items testing this skill. Of these, five correctly answered both items for each of Skills 3 and 4 without any instruction



Teach Skill(s):	2	3 & 4	2 & 3	2 & 4
Test Skill:	2,3 & 4	2,3 & 4	3 & 4	3 & 4
Teach Skill:		2		
Further Test Skills:		2,3 & 4		

Figure 8. Experimental design used to collect additional data on Skills 2, 3 and 4.

Table 6

Additional Data for Skills 2, 3 and 4

Group	Subject	Number of Items Correct for Skill 2	Skill 3	Skill 4
A (taught Skill 2 only)	1	2	2	2
	2	2	2	2
	3	2	0	0
	4	2	2	2
	5	2	0	0
	6	2	0	0
	7	2	0	1
	8	2	2	2
	9	2	0	0
	10	2	0	0
	11	2	0	1
	12	2	2	2
B (after teaching Skills 3 & 4 only)	13	0	0	0
	14	0	0	0
	15	0	0	0
	16	0	0	0
	17	0	0	0
	18	0	0	0
	19	0	0	0
	20	0	0	0
	21	0	0	0
	22	0	0	0
	23	0	0	0
	24	0	0	0
	25	0	0	0
	26	0	0	0

Table 6 (Cont'd)

Group	Subject	Number of Items Correct for Skill 2	Skill 3	Skill 4
B (after teaching Skill 2 in addition)	13	2	2	2
	14	2	2	2
	15	2	2	2
	16	2	0	0
	17	2	2	2
	18	2	2	2
	19	2	2	2
	20	2	2	2
	21	2	1	1
	22	2	2	2
	23	2	2	2
	24	2	0	2
	25	2	2	2
	26	2	2	2
C (taught Skills 2 and 3)	27	2	2	0
	28	2	2	2
	29	2	2	2
	30	2	2	2
	31	2	2	2
	32	2	2	2
	33	2	2	0
	34	2	2	2
	35	2	2	2
	36	2	2	0
	37	2	2	2
	38	2	2	2
	39	2	2	0
	40	2	2	2
	41	2	2	2

Table 6 (Cont'd)

Group	Subject	Number of Items Correct for Skill 2	Skill 3	Skill 4
D (taught Skills 2 and 4)	42	2	2	2
	43	2	2	2
	44	2	2	2
	45	2	0	2
	46	2	2	2
	47	2	2	2
	48	2	2	2
	49	2	2	2
	50	2	2	2
	51	2	2	2
	52	2	2	2
	53	2	2	2
	54	2	2	2
	55	2	2	2
	56	2	2	2
	57	2	2	2

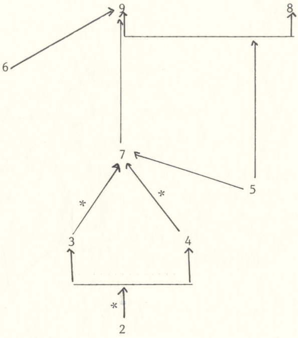
on these skills. In contrast, all 14 subjects instructed on Skills 3 and 4 without prior instruction on Skill 2 failed to correctly answer any item for Skills 2, 3 and 4. Further, when these subjects were then taught Skill 2 and retested on all three skills all were successful on both items for Skill 2, 86% were successful on both items for Skill 3 and 79% were successful on both items for Skill 4. Collectively, the above results suggest not only that Skill 2 must be taught before Skills 3 and 4 but also that learning Skill 2 produces substantial transfer to the learning of Skills 3 and 4.

With respect to the relationship between Skills 3 and 4, all subjects taught Skills 2, 3 only (N=15) and all subjects taught Skills 3, 4 only, were successful on the skills taught. Of those not taught Skill 3, only one failed to exhibit it, while of those not taught Skill 4 none failed to exhibit it. The unit-normal-curve deviate for the difference between the proportions of these two examples exhibiting both skills is 1.60, indicating that there is no difference between these proportions at the .05 level of significance. The number of subjects in each sub-sample is very small, but the data appear to suggest quite conclusively that Skill 2 is subordinate to Skills 3 and 4 and that Skills 3 and 4 are equivalent.

Finally, although it was hypothesized that Skill 1 (Molecular Formula) is logically prerequisite to Skill 2 (Molar Mass), the results show otherwise. They indicate that the ability to interpret a molecular formula in terms of the number of moles of each element in it, is not needed to calculate the molar mass of a compound. In retrospect it is clear that while it may be desirable for meaningful learning that the learner should have an understanding of Skill 1 before he is exposed to Skill 2, it is not essential. It is quite possible that the learner may be able to correctly combine subscripts in a molecular formula with relevant molar masses to calculate the molar mass of a compound, without necessarily understanding what is implied in these values.

From the above results it can be tentatively concluded that research question one has been answered negatively. Application of the White and Clark test and the ordering-theoretic method to the data indicates that the hypothesized hierarchy is not supported in its entirety. However, research question two has been answered positively. An alternative hierarchy (Hierarchy Two) which is composed of a subset of the skills represented in the hypothesized hierarchy is proposed. This alternative hierarchy is represented in Figure 9.

It is suggested that because Hierarchy Two was derived from consideration of skills in pairs, it remains only as a composite and as such is not tested directly. In light of this, the suggestion is made that it is desirable to test the validity of Hierarchy Two as a complete entity. In principle this may be effected by application of the Dayton and Macready method. However, at present only hierarchies with 20 or less true response patterns may be accommodated by the statistical program involved. Hence, the method was applied to smaller components than the complete hierarchy under test. These are referred to as sub-hierarchies. The goodness of fit of these sub-hierarchies to the data is reported in the next section. In addition to the sub-hierarchies derived directly from Hierarchy Two, potentially viable alternatives were also considered where connections were marginally denied according to the White and Clark test. The Dayton and Macready method allows a direct test of hierarchies composed of the same skills in different arrangements. For completeness, Skills 2, 3 and 4 were



9 - Mass to Mass (Excess)
8 - Moles to Moles (Excess)
7 - Mass to Mass
6 - Conservation of Mass
5 - Moles to Moles
4 - Moles to Mass
3 - Mass to Moles
2 - Molar Mass

Note: * indicates that the connection is considered valid only as a result of the additional testing done on Skills 2, 3 and 4.

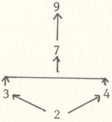
Figure 9. Hierarchy Two.

included in this analysis. However, the primary data relating to these skills were those obtained in the additional study already described.

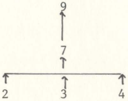
The Dayton and Macready Method

The Dayton and Macready method was described in chapter two. Goodness of fit between data and hypothesized hierarchy is determined by a likelihood ratio expressed as a chi-square. In computing the value of the likelihood ratio, the Dayton and Macready method yields estimates of the guessing and forgetting parameters needed to provide a fit between data and hierarchy. As these values increase, confidence in the particular hierarchy decreases. They may be used to aid differentiation between alternative hierarchies, although the primary statistic is the likelihood ratio. Alternative hierarchies containing the same skills are compared by considering the difference between their likelihood ratios.

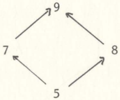
Following consideration of the connections involved between the skills in Hierarchy Two, Sub-Hierarchies Three to Eight, as represented in Figure 10 are suggested as being necessary to test the validity of Hierarchy Two. The null hypothesis under test is that there is no significant difference between the observed frequencies and those expected if the sub-hierarchy in question is considered valid. In all cases the 5% confidence level was applied. In order for a sub-hierarchy to be considered consistent with the data it is necessary that the chi-square value be smaller than the tabular value represented at the 5% confidence level corresponding to the appropriate number of degrees of freedom. The larger the value of the significance level



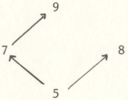
Sub-Hierarchy Three



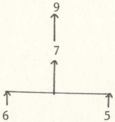
Sub-Hierarchy Four



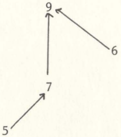
Sub-Hierarchy Five



Sub-Hierarchy Six



Sub-Hierarchy Seven



Sub-Hierarchy Eight

Figure 10. Sub-Hierarchies Three to Eight.

reported the more consistent is the fit of the sub-hierarchy with the data.

To investigate whether Skill 2 (Molar Mass) is equivalent to Skill 3 (Mass to Moles) and Skill 4 (Moles to Mass) as shown by the White and Clark test, or subordinate to Skills 3 and 4 as represented in both the hypothesized hierarchy and Hierarchy Two, Sub-Hierarchies Three and Four were compared for their goodness of fit with the data. The values of the misclassification parameters and likelihood ratios for these two hierarchies are given in Table 7. They indicate that both sub-hierarchies are consistent with the data at the 5% level of confidence. To determine if the fit of either hierarchy was better than the other, Sub-Hierarchies Three and Four were further tested by examining the significance of the difference between their likelihood ratios derived from the Dayton and Macready test. The results of applying this test are reported in Table 8. Δ represents the difference between the likelihood functions for Sub-Hierarchies Three and Four. The number of degrees of freedom associated with the difference between the likelihood functions is equal to the difference between the degrees of freedom for the two sub-hierarchies when they are considered separately. The significance of the difference is determined by reference to a chi-square table. A chi-square value equal to or larger that at the tabulated 5% confidence level would imply that there is a significant difference between Sub-Hierarchies Three and Four. The result shown in Table 8 indicates that no significant difference exists. Hence, from the main data, it is not possible to favor either of the hierarchical arrangements for Skills 2, 3 and 4 represented in Sub-Hierarchies Three and Four over the other. However, the data are consistent with the hypothesis that collectively Skills 2, 3 and 4 are

Table 7

Dayton and Macready Analysis: Likelihood and Misclassification

Parameter Estimates for Sub-Hierarchies Three and Four

Sub-hierarchy	Guessing Parameter Estimate	Forgetting Parameter Estimate	Maximum Likelihood Estimate	Degrees of Freedom	Significance Level at which Sub-Hierarchy is Consistent with Data
3	.04	.00	0.46	23	> 0.99
4	.04	.00	0.45	22	> 0.99

Table 8

Likelihood Ratio Difference for Sub-Hierarchy Three Against

Sub-Hierarchy Four as an Alternative

Alternative Sub-Hierarchy	Maximum Likelihood Estimate	df	Significance Level of N Difference Between Maximum Likelihood Estimates
3	0.46	23	
4	0.45	22	
	Δ = 0.01	1	NS

subordinate to Skill 7 and that Skill 7 is subordinate to Skill 9.

A comparison between the goodness of fit of the data to Sub-Hierarchies Five and Six allowed a test of whether Skill 8 is equivalent to Skill 9 as represented in Hierarchy Two, or subordinate to Skill 9 as represented in the hypothesized hierarchy, as well as testing the relationship between Skills 5, 7 and 8.

The misclassification parameters and the likelihood ratios which resulted from this analysis are represented in Table 9. The results reported for these three sub-hierarchies indicate that the fit of each of those sub-hierarchies is consistent with the data at the 5% level. Again, as with Sub-Hierarchies Three and Four, Sub-Hierarchies Five and Six were compared by examining the significance of the difference between their likelihood ratios. Table 10 indicates that the difference is not significant at the 5% level. Further, the misclassification parameters for Sub-Hierarchies Five and Six, as reported in Table 9, are approximately the same. Hence, they cannot be used to support the superiority of one sub-hierarchy over the other. For these reasons, application of the Dayton and Macready test suggests that it is not necessary to learn Skill 8 before Skill 9. However, Skill 5 is subordinate to Skills 7 and 8, and Skill 7 is subordinate to Skill 9.

To investigate whether Skill 6 (Conservation of Mass) is subordinate to Skill 7 (Mass to Mass) as represented in the hypothesized hierarchy or subordinate to Skill 9 (Mass to Mass (Excess)) as represented in Hierarchy Two, Sub-Hierarchies Seven and Eight were compared for their goodness of fit to the data. The values of the misclassification parameters and likelihood ratios for these two sub-hierarchies

Table 9

Dayton and Macready Analysis: Likelihood and Misclassification

Parameter Estimates for Sub-Hierarchies Five and Six

Sub-Hier-archy	Guessing Parameter Estimate	Forgetting Parameter Estimate	Maximum Likelihood Ratio	Degrees of Freedom	Significance Level at which Sub-Hierarchy is Consistent with Data
5	.00	.05	3.91	8	> 0.80
6	.00	.03	3.12	7	> 0.80

Table 10

Likelihood Ratio Difference for Sub-Hierarchy Five Against Sub-Hierarchy Six as an Alternative

Alternative Sub-Hierarchy	Maximum Likelihood Estimate	df	Significance of the Difference Between Maximum Likelihood Estimates
5	3.91	8	
6	3.12	7	
	Δ = 0.79	1	NS

are given in Table 11. Both sub-hierarchies are consistent with the data at the 5% level of significance. Sub-Hierarchies Seven and Eight were further tested by examining the significance of the difference between their likelihood ratios derived from application of the Dayton and Macready test to the data. The results of applying this test are reported in Table 12. The difference for this comparison is significant at the 5% level of confidence. Hence, application of the Dayton and Macready test suggests that it is not necessary to learn Skill 6 before Skill 7, but that it is necessary to learn Skill 6 before Skill 9.

Earlier it was indicated that, on the basis of the application of the White and Clark test to the data, research question two had been answered positively. In other words, a psychometrically valid hierarchy of intellectual skills had been identified for the concept stoichiometry, at least when these skills are considered in pairs. This same hierarchy is also consistent with the data when the Dayton and Macready method is applied to the group of these same intellectual skills.

In chapter two it was indicated that the validity of a learning hierarchy should be considered in terms of both its psychometric and transfer characteristics. In the section which follows transfer of learning from subordinate to related superordinate skills in Hierarchies One and Two will be examined.

Transfer of Learning from Subordinate to Superordinate Skills

Research question three is concerned with the existence of transfer of learning from subordinate to related superordinate skills in the hypothesized hierarchy.

Table 11

Dayton and Macready Analysis: Likelihood and Misclassification

Parameter Estimates for Sub-Hierarchies Seven and Eight

Sub-Hier-archy	Guessing Parameter Estimate	Forgetting Parameter Estimate	Maximum Likelihood Ratio	Degrees of Freedom	Significance Level at which Sub-Hier-archy is Consistent with Data
7	.09	.03	8.85	8	> 0.30
8	.04	.02	3.05	7	> 0.80

Table 12

Likelihood Ratio Difference for Sub-Hierarchy Seven Against Sub-Hierarchy Eight as an Alternative

Alternative Sub-Hierarchy	Maximum Likelihood Estimate	df	Significance Level of the Difference Between Maximum Likelihood Estimates
7	8.85	8	
8	3.05	7	
	$\Delta = 5.80$	1	< 0.05

As indicated in chapter two, Gagné's index, proportion positive transfer, and others like it, is not considered to be an acceptable test of the degree of transfer of learning between skills in a hierarchy. Therefore, an alternate test of transfer devised by Griffiths (1979), and described in chapter three, was used. Essentially, this test was used to investigate the relationship of gain of subordinate skills between the Chemistry Pretest and Chemistry Posttest to gain of related superordinate skills. It should be noted again that both the Chemistry Pretest and the Chemistry Posttest are post-instruction. In order to apply this test of transfer, remedial action was indicated for each individual student for any skills missed on the Chemistry Pretest. The actual procedures used in the test of transfer and remediation were described in chapter three. Briefly, each student was given an instructional booklet which contained further instruction on the skills in the hypothesized hierarchy, and appropriate exercises for these skills. Indicated in the instructional booklet were the skills for which each subject was weak, as evidenced by performance on the Chemistry Pretest. Subjects were requested to cover the appropriate sections before the Chemistry Posttest was administered. From the posttest it was determined if students had gained subordinate skills and/or superordinate skills between the Chemistry Pretest and Chemistry Posttest. The significance of the relationship between Gain/No Gain on subordinate skills and Pass/Fail on the related superordinate skills was then determined by application of a chi-square test, with one degree of freedom in each case.

The results of applying the test of transfer in the manner described above are presented in Table 13. It should be noted that any connections involving Skills 2 and 3, or 4 were omitted from Table 13

Table 13

Test of Transfer from Subordinate to Superordinate Skills

Connection	No Gain Fail (N)	No Gain Pass (N)	Gain Fail (N)	Gain Pass (N)	χ^2	df	Significance
8 to 9	8	1	2	13	13.2	1	< 0.001
7 to 9	11	1	1	8	13.6	1	< 0.001
6 to 9	3	0	5	6	2.86	1	> 0.05
6 to 7	2	0	4	5	1.85	-	> 0.10
5 to 8	2	1	0	5	4.44	-	< 0.05
5 to 7	2	0	3	2	1.12	-	> 0.20

because the proportion of subjects failing to exhibit these was too small to allow for meaningful interpretation of a transfer effect.

Significant transfer of learning was found from Skill 8 to Skill 9 ($p < .001$). This implies that understanding of Skill 8 will significantly aid the learning of Skill 9, and hence that Skill 8 may be usefully taught before Skill 9. Based on this, it is suggested that when having to choose between Sub-Hierarchies Five and Six, which have different arrangements of Skills 8 and 9, but have equally consistent fit with the data, the sub-hierarchy which represents Skill 8 as being subordinate to Skill 9 should be favored. Hence, Sub-Hierarchy Five which shows Skill 8 as being subordinate to Skill 9 is suggested as being the more acceptable alternative of the two sub-hierarchies under discussion.

The results in Table 13 also indicate significant transfer of learning between Skill 7 (Mass to Mass) and Skill 9 (Mass to Mass (Excess)) ($p < .001$), implying that understanding of Skill 7 significantly aids the learning of Skill 9, and hence that Skill 7 may be usefully taught before Skill 9.

A surprising result reported in Table 14 concerns the transfer of learning between Skill 6 (Conservation of Mass) and Skill 9 (Mass to Mass (Excess)). It indicates ($p > .05$) that any transfer of learning between Skill 6 and Skill 9 is not significant. Hence, the test of transfer denies the existence of a hierarchical connection between Skills 6 and 9. This implies that the ability to correctly exhibit Skill 9 does not depend upon understanding that such calculations depend upon the validity of the Law of Conservation of Mass. This result is in opposition to the results reported by the two psychometric tests used in this study, which support the validity of a hierarchical connection between Skills 6 and 9.

Table 13 further indicates that any transfer of learning between Skills 6 (Conservation of Mass) and 7 (Mass to Mass) is not significant ($p > .10$). Hence, the test of transfer, as with the two psychometric tests used in this study, denies the existence of a hierarchical connection between Skills 6 and 7. This implies that the ability to correctly exhibit Skill 7 not only does not depend upon understanding that such calculations depend upon the validity of the Law of Conservation of Mass, but also that learning of Skill 6 does not significantly enhance learning of Skill 7.

With respect to the relationship between Skill 5 (Moles to Moles) and Skill 8 (Moles to Moles (Excess)), Table 14 ($p < .05$) indicates significant transfer of learning exists from Skill 5 to Skill 8, which implies that understanding of Skill 5 will significantly aid the learning of Skill 8.

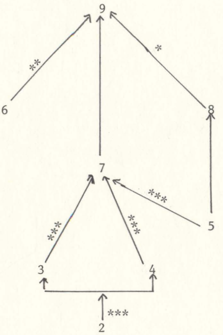
Finally, the result reported in Table 14 for the relationship between Skill 5 (Moles to Moles) and Skill 7 (Mass to Mass) ($p > 0.20$), suggests that no significant transfer of learning exists from Skill 5 to Skill 7. However, it is suggested that the small number of subjects available to test this connection mitigates against finding transfer.

In chapter two the view was expressed that a hierarchy validated by either the psychometric or transfer definition of hierarchical dependency, but not both, should be regarded as incompletely validated. However, it is now suggested that such a stringent criterion may result in some connections which can provide valuable information being dismissed too readily. For example, in the present study the connection between Skills 6 and 9, discussed above, which is considered valid by the psychometric definition but not the transfer definition, and the connection between Skills 5 and 7, which is considered valid by the psychometric definition but not the transfer definition, are two examples where the requirement would result in substantial loss of information.

Accordingly, it is suggested that connections which are considered valid by either one, but not both of the definitions of hierarchical dependency should be included in any resultant hierarchy but should be designated in such a way that it is clear which one of the definitions of hierarchical dependency is implied. Doing so would result in a "preferred hierarchy" in which some connections are considered valid by both the psychometric and transfer definitions of hierarchical dependency, while other connections are considered valid by only one of the definitions of hierarchical dependency. It is then left to the user to assess the findings as they are reported in the hierarchy, and to use them as he wishes. Hierarchy Three (shown in Figure 11) represents the "preferred" hierarchy resulting from the present study. It is represented more fully in Figure 12, and is discussed in the next section.

The Structure of the Preferred Hierarchy

Hierarchy Three exhibits similarities to, and differences from, the hypothesized hierarchy. Of the eight skills hypothesized to be subordinate to Skill 9 (Mass to Mass (Excess)), all skills were found to be subordinate, either in a psychometric sense or a transfer sense, or both. However, Skill 1 (Molar Mass) was eliminated because it was clear from the data that it was not necessary that the learner need be

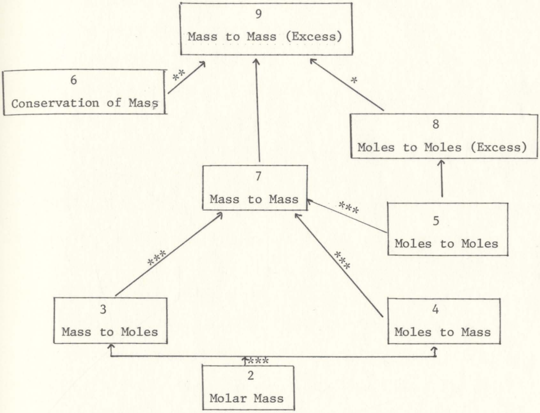


Note: 1) * indicates that the connection is considered valid by only the transfer definition of hierarchical dependency.

2) ** indicates that the connection is considered valid by only the psychometric definition of hierarchical dependency.

3) *** indicates that due to the small number of subjects involved, the results obtained from the test of transfer for these connections cannot be meaningfully interpreted. Hence, although these connections are considered psychometrically valid, no decision can be made with respect to transfer validity.

Figure 11. Hierarchy Three.



Note: 1) * indicates that the connection is considered valid by the transfer definition of hierarchical dependency only.

2) ** indicates that the connection is considered valid by the psychometric definition of hierarchical dependency only.

3) *** indicates that due to the small number of subjects involved, the results obtained from the test of transfer for these connections cannot be meaningfully interpreted. Hence, although these connections are considered psychometrically valid, no decision can be made with respect to transfer validity.

Figure 12. The Preferred Hierarchy.

able to determine the number of moles of each element in a compound (Skill 1) before he can calculate the molar mass of a compound (Skill 2). Hence, the learner can apply the numerical values in a molecular formula, to the calculation of a molar mass without necessarily understanding what is implied by these values.

Some relationships hypothesized to exist between pairs of skills were substantiated using both the psychometric and transfer definitions of hierarchical dependency. Such relationships were observed between Skills 7 and 9 and between Skills 5 and 8. The ability to exhibit Skill 9 (Mass to Mass (Excess)) required, as hypothesized, the ability to demonstrate an understanding of how to calculate the mass of a product or reactant when given a balanced chemical reaction and the mass of a different reactant (Skill 7). Further, Skill 7 facilitated learning of Skill 9, as evidenced by a substantial transfer effect. Similarly, performance of problems involving mole quantities (Skill 5) were necessary for, and facilitated learning of limiting reagent problems involving mole problems (Skill 8).

One connection was found to be valid in terms of the transfer definition but not the psychometric definition. The ability to perform limiting reagent problems for mole relationships (Skill 8) facilitated acquisition of correct performance of mass-mass limiting reagent problems (Skill 9). Such a finding seems to be of substantial significance for the arrangement of instruction leading to the acquisition of Skill 9. It is surprising that a similar relationship appears not to exist between Skills 5 and 7. However, where a number of skills are simultaneously subordinate to a particular skill in a hypothesized hierarchy (i.e., where several branches simultaneously converge) the existence of transfer for any individual connection is more difficult to establish because of the influence of the other connections. Also, as noted previously, very few subjects were available to test this connection. According to Table 3 at least 5.6% of the sample correctly performed mass-mass stoichiometric calculations (Skill 7) without exhibiting understanding that mass is conserved in a chemical reaction (Skill 6), a finding that should cause concern for educators. However, the more difficult Skill 9 (Mass-Mass (Excess)) did require the ability to apply the Law of Conservation of Mass.

Another relationship hypothesized to exist between a pair of skills was substantiated only when the less stringent view of hierarchical dependency was adopted. It was hypothesized that the ability to exhibit Skill 7 (Mass to Mass) required the ability to demonstrate an understanding of how to calculate the number of moles of a product or reactant when given a balanced chemical equation and the number of moles of a different reactant (Skill 5). This relationship was substantiated by the psychometric definition of hierarchical dependency, but as indicated previously, because of the small numbers involved, could not be tested according to the transfer definition of hierarchical dependency.

Finally, it was originally hypothesized that Skill 2 (Molar Mass) was subordinate to the equivalent Skills 3 (Mass to Moles) and 4 (Moles to Mass), which in turn were subordinate to Skill 7 (Mass to Mass). This connection was found to be valid in terms of the psychometric definition but could not be tested by the transfer definition because the proportion of subjects failing to exhibit Skills 2, 3 and 4 was too small to allow for a meaningful interpretation of the results.

In concluding this chapter a discussion of subjects' misconceptions, as evidenced from an analysis of incorrect items testing specific skills pertaining to the stoichiometric concept will be given in the next and final section.

Subjects' Misconceptions Relating to Specific Skills Pertaining to the Concept of Stoichiometry

Research question four is concerned with identification of common misconceptions relating to the chemistry skills under study. When answering the chemistry test items students were asked to show all of their working. When the items were marked by the investigator incorrect solutions were critically examined for types of conceptual errors. This 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 given were treated as missing data. Generally, subjects were very co-operative in showing the steps in their calculations.

Analysis of the steps used in calculating incorrect responses for items revealed that many subjects held common fundamental misconceptions. In the discussion which follows, a description of these misconceptions will be given, together with the number and percentage of subjects who exhibited each particular misconception for each particular skill. Any one error exhibited by an individual subject was counted only once, even though the same error may have occurred in both items testing the same skill. Where a subject made different errors on the items testing the same skill each separate error was indicated. Finally, it is worth noting that 5% of the sample of 180 subjects did not make any errors on the Chemistry Pretest.

Skill 1 (Molecular Formula)

Subjects exhibited a number of misconceptions in attempting to *state the number of moles of each element present in one mole of a compound when given the molecular formula for the compound.* These misconceptions are given in Table 14. A major misconception, exhibited by 14% of the subjects, was the assumption that in one mole of a substance, regardless of the numerical values present for each element in the chemical formula, the mole ratio of one element to another is always one to one. A second misconception, exhibited by 12% of the subjects, was that what was required was calculation of either the total mass of each element present in the compound, or the molar mass of the compound. Other subjects (6%) applied a strategy which involved placing the number of moles of each individual element in the compound over a composite mole quantity obtained by adding together the subscripts representing the number of moles of each element present in the compound. A smaller proportion of the subjects (2%) added together the subscripts representing the number of moles of each element present in one mole of the compound, and gave this composite mole quantity as the answer. Another misconception, exhibited by 5% of the subjects, resulted in these subjects first devising a balanced chemical equation to represent the formation of one mole of the given compound, and then giving the coefficient from the resultant balanced chemical equation for each element in the answer. Finally, some subjects (3%), applied the last subscript to other elements represented in the formula.

The large number of subjects who exhibited misconceptions for Skill 1 suggests that many students do not meaningfully understand what the numerical values in a chemical formula represent in terms of

Table 14

Subjects' Misconceptions on Skill 1 (Molecular Formula)

Misconception Number	Misconception	No. of Subjects	%
1	Disregarding subscripts	24	14
2	Calculating the mass present in each element of the compound or its molar mass	27	12
3	Dividing subscripts of one element by total of all subscripts	10	6
4	Naming the stoichiometric equation coefficients in a balanced chemical equation	8	5
5	Application of last subscript to other elements	6	3
6	Addition of all subscripts	5	2

Note: All of the statistics in this table and others similar to it are based on a sample of 180 subjects to whom the tests were administered.

the number of moles of each element present. While this skill does not feature in the preferred hierarchy this widespread lack of understanding is alarming.

Skill 2 (Molar Mass)

Table 15 indicates the misconceptions exhibited by subjects in attempting to *calculate the molar mass of a compound when given its chemical formula.* Most subjects had little difficulty with the items testing this skill. Four percent assumed a 1:1 mole ratio of the elements in a compound when calculating the molar mass of that compound, thus disregarding the subscripts entirely. A small proportion, 2%, applied the last subscript to other elements represented in the formula.

Skill 3 (Mass to Moles)

Misconceptions exhibited for Skill 3, *given the mass and formula of a compound, calculate the number of moles present,* are indicated in Table 16.

Ten percent of the subjects experienced conceptual difficulties with this skill. The difficulty experienced by these subjects arose from the incorrect recall or application of the required algorithm. Instead of dividing the given mass by the molar mass of the named compound in an item, subjects either multiplied the mass by the molar mass, or divided the mass into the molar mass of the compound. One subject, after correctly changing the given mass to its corresponding number of moles, then multiplied this mole quantity by the molar mass of the compound named in the item. It seems possible these subjects

Table 15

Subjects' Misconceptions on Skill 2 (Molar Mass)

Misconception Number	Misconception	No. of Subjects	%
1	Disregarding subscripts	7	4
2	Application of last sub-script to other elements	3	2

Table 16

Subjects' Misconceptions on Skill 3 (Mass to Moles)

Misconception Number	Misconception	No. of Subjects	%
1	Use of an incorrect algorithm	18	10
2	Incorrect calculation of molar mass	7	4
3	Naming the stoichiometric equation coefficients in a balanced chemical equation	4	2

memorized the algorithm without understanding its components. Hence, they were more likely to apply it incorrectly. A further 4% calculated the molar mass of the given compound incorrectly, either because they disregarded the subscripts or applied the last subscript to other elements in the formula. Finally, a small proportion (2%) of the subjects devised a balanced chemical equation to represent the formation of one mole of the given compound, and then gave the coefficients from the resultant balanced chemical equation for each element as the answer.

Skill 4 (Moles to Mass)

Skill 4 requires that *a given number of moles of a compound be changed to its corresponding mass, given the chemical formula for the named compound.* As this skill involves the same components in the opposite direction to those in Skill 3 (Mass to Moles) it is not surprising to find similar misconceptions. The percentage of subjects exhibiting these misconceptions for Skill 4 are given in Table 17.

As for Skill 3, 10% of the subjects exhibited incorrect recall or application of the appropriate algorithm. Instead of multiplying the given number of moles of the named compound by its molar mass, subjects either divided the molar mass into the given number of moles, or did the opposite. Again this suggests that the algorithm is not understood by these subjects. Also, a further 7% of the subjects calculated the molar mass of the named compound incorrectly for the same reasons as discussed with Skill 3 (Mass to Moles).

Before ending the discussion of subjects' misconceptions relating to Skills 2, 3 and 4 it should be noted that most subjects had little difficulty with these skills. Ninety-two percent of the

Table 17

Subjects' Misconceptions for Skill 4 (Moles to Mass)

Misconception Number	Misconception	No. of Subjects	%
1	Use of an incorrect algorithm	18	10
2	Incorrect calculation of molar mass	12	7

subjects exhibited correct responses to the items testing Skill 2, 82% exhibited appropriate responses for Skill 3 and 83% exhibited correct responses for Skill 4.

Skill 5 (Moles to Moles)

Skill 5 represents the ability to *calculate the number of moles of a designated substance when given the number of moles of one other reactant or product and the balanced chemical equation for the reaction.* Subjects' misconceptions evidenced in their attempts to do the items representing this skill are given in Table 18. The major misconception, exhibited by 17% of the subjects, involved failure to use the stoichiometric relationship from the given balanced chemical equation. These subjects used a variety of approaches. Some subjects multiplied the given number of moles of the reactant by the molar mass of the desired product. Others divided the molar mass of the product into the given number of moles, or did the opposite. One subject added up the number of moles of each element in the desired product and gave this composite quantity as the answer. Another multiplied the given number of moles by this composite quantity to obtain an answer. In none of the cases reported above was any attempt made to use the stoichiometric relationship expressed in the equation, thus indicating that these subjects had no understanding of the nature of the relationships between the coefficients in a balanced chemical equation and the actual numbers of moles of the substances involved in the reaction.

Some subjects (7%) used stoichiometric coefficients, but in a wrong combination or incompletely. Of these, almost half multiplied the stoichiometric coefficients by the given number of moles of reactant.

Table 18

Subjects' Misconceptions for Skill 5 (Moles to Moles)

Misconception Number	Misconception	No. of Subjects	%
1	Failure to use the given balanced chemical equation	31	17
2	Inappropriate use of stoichiometric coefficients	13	7
3	Use of wrong reactant or product	6	4

Finally, 4% of the subjects employed the wrong stoichiometric relationship. In every case, the correct reactant was included in the relationship, but not the desired product. Consequently, the correct stoichiometric coefficient was present for the reactant, but not for the product. In every case where this misconception was exhibited, subjects used the incorrect stoichiometric relationship and the number of moles of the reactant given in the item to calculate a correct answer for the stoichiometric relationship they used.

Skill 6 (Law of Conservation of Mass)

Skill 6 involves the implicit application of the Law of Conservation of Mass by requiring the subject to *find the missing mass in a reaction when given the masses of all other substances involved in the reaction and the balanced chemical equation for the reaction.* Although the chemical equation for the reaction was given, all that was necessary to correctly solve the items testing this skill was to determine the difference between the total masses given for each side of the equation. However, for consistency with other items the equation was given. Only one consistent misconception was observed. It is represented in Table 19. Thirty-three percent of the subjects incorrectly used an algorithm, which made use of the given balanced chemical equation. Seventy percent of these subjects simply calculated the molar mass of one or more of the compounds in the given equation and gave this as their answer. Others, using a stoichiometric relationship from the equation, set up a proportion which incorporated the stoichiometric coefficients for a reactant and the desired product and the molar mass of the reactant. Using this, they attempted to calculate the required mass of the unknown product. Some subjects added up the

Table 19

Subjects' Misconceptions for Skill 6 (Law of Conservation of Mass)

Number of Misconception	Misconception	No. of Subjects	%
1	Incorrect application of an algorithm	57	33

masses of the reactants given in the item, placed this composite mass over the molar mass of one of the reactants, and converted it to a mole quantity which was then used in a stoichiometric relationship involving the reactant and the desired product. Some, using a mass quantity given in an item, converted it to an incorrect mole quantity through use of an incorrect molar mass. This mole quantity was then used in a proportion involving a correct stoichiometric relationship. These results suggest that at least one-third of the sample do not understand that mass is conserved in a chemical equation.

Skill 7 (Mass to Mass)

The misconceptions which students exhibited when they attempted to *calculate the mass of a designated product given the mass of a specified reactant, and the balanced chemical equation for the reaction,* are listed in Table 20. Twenty-four percent of the subjects exhibited a misconception which was common to Skill 5 (Moles to Moles). These subjects made no use of the stoichiometric coefficients in the balanced chemical equation given in the item. Nine percent correctly calculated molar masses for reactants and products, but failed to multiply the molar mass of each substance by its stoichiometric coefficient before calculating the unknown mass. Instead of expressing all quantities as moles or masses, 8% combined mole and mass quantities together without discriminating between them. A further 15% of the subjects calculated the molar masses of compounds incorrectly either because they assumed a 1:1 to mole ratio of constituent elements or applied the last subscript to the other elements in the formula. Finally, a small proportion of the subjects (2%) exhibited a misconception which arose from

Table 20

Subjects' Misconceptions for Skill 7 (Mass to Mass)

Number of Misconceptions	Misconception	No. of Subjects	%
1	Failure to use the provided balanced chemical equation	42	24
2	Failure to multiply molar mass by stoichiometric coefficient	16	9
3	Indiscriminate combination of mass and mole quantities	14	8
4	Incorrect calculation of molar mass	26	15
5	Use of an incorrect algorithm for converting mass to moles	4	2

the incorrect recall or application of the required algorithm used to calculate the number of moles of a compound present in a given mass. These subjects either multiplied the given mass by the molar mass, or divided the mass into the molar mass of the compound, instead of dividing the given mass by the molar mass of the compound concerned.

Skill 8 (Moles to Moles (Excess))

Skill 8 is concerned with *calculating the number of moles of a designated product, given a balanced chemical equation and the number of moles of two reactants, one of which is in excess*. Major misconceptions are shown in Table 21. As was found for Skill 5 (Moles to Moles) and Skill 7 (Mass to Mass) previously, many subjects (17%) attempted to obtain a response without giving any consideration to the stoichiometric relationships in the balanced chemical equation. Fourteen percent of the subjects either summed the given mole quantities of the reactants and then attempted to combine this sum with the stoichiometric relationship from the equation, or summed the given mole quantities and the stoichiometric coefficients for the two reactants separately and then used these together with the stoichiometric coefficient of the desired product, to determine the number of moles of product. Ten percent of the subjects selected the wrong substance as the limiting reagent. Seven percent of the subjects failed to distinguish between mole and mass quantities, and hence combined them inappropriately. This misconception was seen previously with Skill 5 (Moles to Moles) and Skill 7 (Mass to Mass). A small proportion of the subjects (4%) calculated the number of moles of product which could be formed by each of the given number of moles of

Table 21

Subjects' Misconceptions for Skill 8 (Moles to Moles (Excess))

Number of Misconception	Misconception	No. of Subjects	%
1	Failure to use the provided balanced chemical equation	30	17
2	Inappropriately summing mass or mole quantities of reactants	25	14
3	Selecting the wrong substance as limiting reagent	18	10
4	Confusing mass and mole quantities	12	7
5	Failure to choose any reagent as limiting reagent	6	4

the reactants and then gave these two mole quantities as the answer. What this implies is that these subjects failed to show understanding of the notion that the quantity of one reactant in a chemical reaction is influenced by the amount of any other reactant present.

Skill 9 (Mass to Mass (Excess))

The misconceptions subjects exhibited when attempting to *calculate the mass of a designated product, given a balanced chemical equation and the masses of two reactants, one of which is in excess*, are shown in Table 22. Many of the misconceptions exhibited by subjects for Skill 8 (Moles to Moles (Excess)) are also common to Skill 9. This is expected as Skill 9 is similar in nature to Skill 8, the only difference being that the values for the reactants are expressed as mass quantities rather than mole quantities. A common misconception exhibited by 26% of the subjects was the selection of the wrong limiting reagent from the two given. Hence, a large proportion of the sample failed to show understanding of the notion that the quantity of one reactant which actually reacts in a chemical reaction is influenced by the quantity of the other reactant(s) present. As was observed for Skill 8, a number of subjects (15%) failed to use the stoichiometric coefficients at all. Instead, these subjects simply converted the larger of the two given masses to its corresponding mole quantity and then multiplied this mole quantity by the molar mass of the desired product. Another misconception, common to Skills 8 and 9, was exhibited by 14% of the students answering the items testing Skill 9. This was the belief that quantities of reactants could be summed and that these composite values could somehow be used to determine the quantity of

Table 22

Subjects' Misconceptions for Skill 9 (Mass to Mass (Excess))

Number of Misconception	Misconception	No. of Subjects	%
1	Selecting the wrong substance as limiting reagent	46	26
2	Failure to use the provided balanced chemical equation	27	15
3	Inappropriate summing masses of reactants	25	14
4	Confusing mole and mass quantities	17	10
5	Incorrect calculation of molar mass	7	4
6	Failure to choose a limiting reagent	4	2

the desired product. Ten percent of the subjects failed to distinguish between mole and mass quantities, and hence combined them inappropriately. A small proportion of the subjects (2%) calculated the molar mass of the compound(s) named in the equation improperly. Finally, some subjects (2%) failed to chose any reagent as limiting reagent.

From the above misconceptions relating to both Skills 8 and 9, it appears that many students do not understand the meaning of the stoichiometric relationships between the coefficients in a balanced chemical equation, nor the relationship between actual moles of the substances used in a reaction. Also, these misconceptions indicate that subjects are not able to discriminate between an item involving an excess of one reagent (Skills 8 and 9) and one that does not (Skills 5 and 7). These subjects indiscriminately applied the same algorithms to items involving an excess of one reactant as to situations where no excess was involved.

Before ending this section it is necessary to comment on the additional item placed at the end of each part of the Chemistry Pretest and Chemistry Posttest. Essentially, as indicated in chapter three, the intent of these items was to investigate whether some subjects considered the first reagent as the limiting reagent in the items testing Skill 8 (Moles to Moles (Excess)) and Skill 9 (Mass to Mass (Excess)). The items used to test for any hierarchical relationship between Skills 8 and 9 always had the first reagent as the limiting reagent. The additional item on each test had the second reagent as the limiting reagent. Of the 119 subjects who did the extra item for Skill 8, 17% of these obtained an incorrect response for the item because they chose the first reagent as the limiting reagent. An additional 24% of these subjects exhibited an incorrect response because of a misconception other than choosing the wrong substance as the limiting reagent. Sixty-one percent of the subjects who attempted the extra item for Skill 8 chose the correct reagent as the limiting reagent.

Of the 115 subjects who did the extra item for Skill 9, 30% of these obtained an incorrect response for the item because they chose the first reagent as the limiting reagent. An additional 39% of these subjects exhibited an incorrect response because of other misconceptions. Thirty-one percent of the subjects who attempted the extra item for Skill 9 chose the correct limiting reagent.

The above results imply that a substantial proportion of the sample did not automatically consider the first reagent to be the limiting reagent, especially for situations involving mole quantities. However, an alarming proportion did make this mistake.

Summary

The chapter began with a consideration of the validity and reliability of the test items. Data collected from parallel tests comprised of these items were then analyzed by the application of the White and Clark test of inclusion and the ordering-theoretic method. This initial analysis, which resulted in the necessary sifting of the data required before the Dayton and Macready method could be applied, indicated that the results obtained from applying these two tests to the data, although not identical, showed substantial agreement. Further, it indicated that the hypothesized hierarchy was not substantiated. Instead, a hierarchy consisting of eight of the nine skills from the hypothesized hierarchy was proposed as an alternative. The resultant hierarchy was used as a basis for the application of the Dayton and Macready method.

Due to an existing limitation in the Dayton and Macready method it could not be used to test the validity of this alternative hierarchy in its entirety. Instead, Dayton and Macready's test was used to test smaller parts of it, consisting of separate sub-hierarchies, which were examined for their goodness of fit to the data by comparing the likelihood ratios resulting from a comparison of one sub-hierarchy containing several skills to another containing the same skills arranged differently. Sub-hierarchies were then combined as appropriate. The alternative hierarchy, tested as sub-hierarchies in the manner described above, was considered to be consistent with the data.

The validity of this alternative hierarchy was then considered in terms of transfer of learning between hierarchically related skills. Significant transfer of learning was found to exist between a number of the upper skills. However, for lower skills few subjects were available for test because most exhibited the skills on the pretest. Hence, the lower part of the hierarchy could not be validated in terms of transfer. Following the transfer analysis, a "preferred hierarchy," representing psychometric and transfer relationships, was declared.

The chapter concluded with a discussion of subjects' misconceptions of the skills concerned.

CHAPTER 5

SUMMARY, IMPLICATIONS AND RECOMMENDATIONS

Summary

The purpose of the study which has been described was to attempt to identify a valid learning hierarchy involving correct performance of stoichiometric calculations. The ability to do these types of calculations is of central importance in the study of chemistry and a source of difficulty to many high school students.

A learning hierarchy leading to mass-mass stoichiometric calculations was proposed by the investigator and modified after examination by a panel of three science educators. The resultant hierarchy represented the hypothesized hierarchy for the study. Two parallel chemistry tests, each compounded from nine smaller sub-tests, which consisted of four items for each skill in the hypothesized hierarchy, were developed to test the skills represented in the hypothesized hierarchy. After examination by the panel of science educators, minor modifications were made to some items in the tests. Each was pilot-tested, and modified further as a result of feedback gained. The major modification to each test, labelled Chemistry Pretest and Chemistry Posttest, respectively, was a reduction from four to two items testing each skill in the hypothesized hierarchy.

The Chemistry Pretest was administered by the investigator to each class as soon as possible after instruction on the topic was completed by the respective classroom teachers. After examination by the investigator, each subject received his(her) result on the Chemistry Pretest and an instructional booklet which contained the skills on which the subject was deemed weak. Each subject was then asked to complete those sections in the instructional booklet relating to these skills. The instructional booklet contained instruction and appropriate questions relating to each skill in the hypothesized hierarchy. Several days after the instructional booklet was given to the students, the skills in the hypothesized hierarchy were again tested in the Chemistry Posttest, which was also administered by the investigator.

Three statistical tests, the White and Clark test of inclusion, the ordering-theoretic method, and the Dayton and Macready scaling method, were applied to the Chemistry Pretest data in order to determine the psychometric validity of the hypothesized hierarchy. As a result, the hypothesized hierarchy was rejected. However, an alternative hierarchy was suggested. Three lower skills in this hierarchy were subjected to further testing, because too few subjects failed each to allow meaningful interpretation. The relationship between these skills was as originally hypothesized. The upper skills generally showed good transfer between hierarchically related skills. However, for many connections, especially involving the lower skills, the test could not be reasonably applied.

The arrangements of skills represented in Figure 12 was considered to be the preferred hierarchy resulting from this study. This hierarchy contained eight of the nine skills originally represented in the hypothesized hierarchy.

Implications

The study is considered to have implications for the arrangement of instruction for stoichiometric calculations, diagnosis of problems with respect to particular skills relating to performance of stoichiometric calculations, and the methodology of learning hierarchy validation.

1. With respect to the sequencing of instruction leading to understanding of stoichiometric calculations, several implications may be stated. A major implication is that a number of intellectual skills have been identified, each of which is a necessary prerequisite to the correct performance of stoichiometric calculations involving mass or moles. The actual arrangement of these skills is represented in Figure 12.

2. Qualitative examination of subjects' responses to the test items indicated a number of common misconceptions. Further, the analysis revealed that the misconceptions were seen to be consistent over a variety of skills as a learner progressed through the hierarchy. It is suggested that ensuring mastery of each skill before progression to the next skill in the hierarchy will prevent this accumulation of misconceptions.

3. A third implication of the present study relates to the methodology of learning hierarchy validation. Although a number of methods are presently available for hierarchy validation the most promising methods are still experimental. As a result, the safest means at present which will ensure consistent progress being made in the

arrangement of instruction of intellectual skills and articulation of the learning hierarchy model itself, is the analysis of data by several methods. A comparison of the hierarchies emerging from the application of these three psychometric tests to the data indicates that the hierarchies substantiated by the "ordering-theoretic" method and the White and Clark test, although not identical, showed substantial agreement. Further, the alternative hierarchy emerging from the application of the White and Clark test to the data essentially remained unchanged after the Dayton and Macready method was applied to the same data. Hence, the present study suggests that the three methods give similar results. However, such a finding, relating to one study, should be considered to be suggestive only. A particular cause for concern is found in the absence of a completely satisfactory test for transfer. At present no method which is both theoretically pleasing and consistently easy to apply is available.

Suggestions for Further Research

1. The application of the hierarchical model of learning should be applied to the extension of stoichiometric calculations as defined in the present study. For example, the use of molar volumes and ionic calculations in stoichiometric calculations might be profitably investigated through this model.

2. The hierarchical model should be applied to other concepts in physical science, in light of the more appropriate methods now available for learning hierarchy validation, to determine if learning of these concepts can also be accounted for on the basis of the cumulative learning model.

3. The misconceptions identified should be considered in designing instruction relating to stoichiometry.

4. The Dayton and Macready model should be extended to allow for the testing of larger hierarchies and to allow for unrestricted misclassification parameters in situations additional to those involving the concept attainment model.

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APPENDICES

APPENDIX 1

NAME ____________________

SCHOOL____________________

DATE ____________________

GRADE 10 CHEMISTRY TEST

Student Instructions

This is a closed book test. You are asked to answer all of the questions in the space provided on this paper. If you do not have enough space to answer a question, place the remainder of the answer on the reverse side of the page.

It is very important that you show all of your work, as you will lose no marks for any work which is incorrect, only for incorrect or incomplete answers.

If you find that you are having difficulty answering any one question, do not spend too long on it. Proceed to the next question.

Attempt as many questions as you can, even if you cannot complete the whole test.

Please use the following atomic weights:

aluminum (Al) - 27	hydrogen (H) - 1
beryllium (Be) - 9	lithium (Li) - 7
bromine (Br) - 80	magnesium (Mg) - 24
carbon (C) - 12	manganese (Mn) - 55
calcium (Ca) - 40	nitrogen (N) - 14
chlorine (Cl) - 35.5	oxygen (O) - 16
chromium (Cr) - 52	potassium (K) - 39
copper (Cu) - 63.5	sodium (Na) - 23
fluorine (F) - 19	sulfur (S) - 32
iron (Fe) - 56	

1. The molecular formula of barium bromide is $BaBr_2$. How many moles of barium (Ba) and bromine (Br) are contained in one mole of barium bromide?

2. Calculate the mass of potassium nitrate (KNO_3) in 2.0 moles of potassium nitrate.

3. Consider the reaction between calcium fluoride (CaF_2) and hydrogen chloride (HCl) according to the equation:

$$CaF_2 + 2\ HCl \rightarrow CaCl_2 + 2\ HF$$

If 39 grams of CaF_2 and 73 grams of HCl are mixed together and allowed to react until no further reaction occurs, calculate the mass of hydrogen fluoride (HF) produced.

4. Calculate <u>the number of moles of aluminum sulfide (Al_2S_3)</u> in 30 grams of aluminum sulfide.

5. Iron oxide (Fe_2O_3) reacts with carbon (C) according to the equation:

$$2\ Fe_2O_3 + 3\ C \rightarrow 4\ Fe + 3\ CO_2$$

Calculate the <u>number of moles of iron (Fe) produced by 6 moles of Fe_2O_3.</u>

6. Sodium oxide (Na_2O) reacts with hydrogen choloride (HCl) according to the equation:

$$Na_2O + 2\ HCl \rightarrow 2\ NaCl + H_2O$$

Calculate the <u>mass of sodium chloride (NaCl)</u> produced by 31 grams of Na_2O.

7. Calculate the <u>molar mass</u> of beryllium chloride ($BeCl_2$).

8. The reaction between sodium (Na) and hydrogen chloride (HCl) produces sodium chloride (NaCl) and hydrogen gas (H_2):

$$2\ Na + 2\ HCl \rightarrow 2\ NaCl + 1\ H_2$$

What <u>mass of NaCl</u> would be produced if 2.3 grams of Na reacted with 3.65 grams of HCl to produce 0.1 grams of H_2?

9. Consider the reaction between hydrogen gas (H_2) and chromium chloride ($CrCl_3$) according to the equation:

$$3\ H_2 + 2\ CrCl_3 \rightarrow 2\ Cr + 6\ HCL$$

If 4 moles of H_2 and 4 moles of $CrCl_3$ are mixed together and allowed to react until no further action occurs, calculate the <u>number of moles of hydrogen chloride (HCl) produced</u>.

10. Consider the reaction between acetylene (C_2H_2) and oxygen (O_2) according to the equation:

$$2\ C_2H_2 + 5O_2 \rightarrow 4\ CO_2 + 2\ H_2O$$

If 52 grams of C_2H_2 and 32 grams of O_2 are mixed together and allowed to react until no further reaction occurs, <u>calculate the number of grams of carbon dioxide (CO_2) produced</u>.

APPENDIX 2

NAME ____________________

SCHOOL____________________

DATE ____________________

GRADE 10 CHEMISTRY TEST

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beryllium (Be) - 9	lithium (Li) - 7
bromine (Br) - 80	magnesium (Mg) - 24
carbon (C) - 12	manganese (Mn) - 55
calcium (Ca) - 40	nitrogen (N) - 14
chlorine (Cl) - 35.5	oxygen (O) - 16
chromium (Cr) - 52	potassium (K) - 39
copper (Cu) - 63.5	sodium (Na) - 23
fluorine (F) - 19	sulfur (S) - 32
iron (Fe) - 56	

1. The molecular formula of iron oxide is Fe_2O_3. How many moles of iron (Fe) and oxygen (O) are contained in one mole of iron oxide?

2. Calculate the number of moles of ethanol (C_2H_6O) in 69 grams of ethanol.

3. Ethane (C_2H_6) reacts with oxygen gas (O_2) according to the equation:

$$2\ C_2H_6 + 7\ O_2 \rightarrow 4\ CO_2 + 6\ H_2O$$

Calculate the mass of carbon dioxide (CO_2) produced by 15 grams of ethane.

4. Consider the reaction between methane (CH_4) and oxygen (O_2) according to the reaction:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2\ H_2O$$

If 16 grams of CH_4 and 96 grams of O_2 are mixed together and allowed to react until no further reaction occurs, calculate the mass of carbon dioxide (CO_2) produced.

5. Calculate the <u>mass of water (H_2O)</u> in 0.50 mole of water.

6. Calculate the <u>molar mass</u> of calcium carbonate ($CaCO_3$).

7. Consider the reaction between lithium fluoride (LiF) and sodium sulfide (Na_2S) according to the equation:

$$2\ LiF + Na_2S \rightarrow Li_2S + 2\ NaF$$

If 4 moles of LiF and 3 moles of Na_2S are mixed together and allowed to react until no further reaction occurs, calculate the <u>number of moles of sodium fluoride (NaF) produced</u>.

8. The reaction between hydrogen chloride (HCl) and sodium bromide (NaBr) produces sodium chloride (NaCl) and hydrogen bromide (HBr):

$$HCl + NaBr \rightarrow NaCl + HBr$$

What mass of NaCl would be produced if 3.7 grams of HCl reacted with 10.3 grams of NaBr to produce 8.1 grams of HBr?

9. Ammonia (NH_3) reacts with oxygen gas (O_2) according to the equation:

$$4\ NH_3 + 3O_2 \rightarrow 2\ N_2 + 6\ H_2O$$

Calculate the number of moles of nitrogen (N_2) produced by 2 moles of NH_3.

10. Consider the reaction between iron (III) sulfate [$Fe_2(SO_4)_3$] and lithium hydroxide (LiOH) according to the equation:

$$Fe_2(SO_4)_3 + 6\ LiOH \rightarrow 2\ Fe(OH)_3 + 3\ Li_2SO_4$$

If 2 moles of $Fe_2(SO_4)_3$ and 3 moles LiOH are mixed together and allowed to react until no further reaction occurs, calculate the <u>numbers of moles of lithium sulfate (Li_2SO_4) produced</u>.

APPENDIX 3

ITEMS TESTING SKILLS 1 TO 9 CHEMISTRY PRETEST, PARTS ONE AND TWO

	PART ONE	PART TWO
9. Mass to Mass (Excess)	03	04
8. Moles to Moles (Excess)	09	07
7. Mass to Mass B	06	03
6. Mass to Mass A	08	08
5. Moles to Moles	05	09
4. Moles to Mass	02	05
3. Mass to Moles	04	02
2. Molar Mass	07	06
1. Molecular Formula	01	01

APPENDIX 4

NAME ____________________

SCHOOL____________________

DATE ____________________

GRADE 10 CHEMISTRY TEST

Student Instructions

This is a closed book test. You are asked to answer all of the questions in the space provided on this paper. If you do not have enough space to answer a question, place the remainder of the answer on the reverse side of the page.

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bromine (Br) - 80	mangesium (Mg) - 24
carbon (C) - 12	manganese (Mn) - 55
calcium (Ca) - 40	nitrogen (N) - 14
chlorine (Cl) - 35.5	oxygen (O) - 16
chromium (Cr) - 52	potassium (K) - 39
copper (Cu) - 63.5	sodium (Na) - 23
fluorine (F) - 19	sulfur (S) - 32
iron (Fe) - 56	

1. The molecular formula of hydrogen peroxide is H_2O_2. How many moles of hydrogen (H) and oxygen (O) are contained in one mole of hydrogen peroxide?

2. Calculate the number of moles of calcium fluoride (CaF_2) in 39 grams of calcium fluoride.

3. Consider the reaction between lithium fluoride (LiF) and sodium sulfide (Na_2S) according to the equation:

$$2\ LiF + Na_2S \rightarrow Li_2S + 2\ NaF$$

If 26 grams of LiF and 78 grams of Na_2S are mixed together and allowed to react until no further reaction occurs, calculate the mass of lithium sulfide (Li_2S) produced.

4. Butane (C_4H_8) reacts with oxygen (O_2) according to the equation:

$$C_4H_8 + 6O_2 \rightarrow 4CO_2 + 4H_2O$$

Calculate the mass of water (H_2O) produced by 112 grams of butane.

5. Calculate the mass of magnesium chloride ($MgCl_2$) in 3.0 moles of magnesium chloride.

6. Calculate the molar mass of carbon dioxide (CO_2).

7. Consider the reaction between iron (II) chloride ($FeCl_2$) and lithium hydroxide (LiOH) according to the equation:

$$FeCl_2 + 2LiOH \rightarrow 2LiCL + Fe(OH)_2$$

If 2 moles of $FeCl_2$ and 7 moles LiOH are mixed together and allowed to react until no further reaction occurs, calculate the number of moles of lithium chloride (LiCl) produced.

8. Calcium (Ca) combines with sulfur (S) to produce calcium sulfide (CaS) according to the equation:

$$Ca + S \rightarrow CaS$$

What mass of CaS would be produced if 4 grams of Ca and 3.2 grams of S reacted?

9. Copper (Cu) reacts with hydrogen chloride (HCl) according to the equation:

$$Cu + 2HCl \rightarrow CuCl_2 + H_2$$

Calculate the number of moles of copper chloride ($CuCl_2$) produced by 6 moles of HCl.

10. Consider the reaction between magnesium (Mg) and hydrogen chloride (HCl) according to the equation:

$$Mg + 2HCl \rightarrow MgCl_2 + H_2$$

If 48 grams of Mg and 36.5 of HCl are mixed together and allowed to react until no further reaction occurs, calculate the number of grams of hydrogen gas (H_2) produced.

APPENDIX 5

NAME ____________________

SCHOOL____________________

DATE ____________________

GRADE 10 CHEMISTRY TEST

Student Instructions

This is a closed book test. You are asked to answer all of the questions in the space provided on this paper. If you do not have enough space to answer a question, place the remainder of the answer on the reverse side of the page.

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Please use the following atomic weights:

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beryllium (Be) - 9	lithium (Li) - 7
bromine (Br) - 80	magnesium (Mg) - 24
carbon (C) - 12	manganese (Mn) - 55
calcium (Ca) - 40	nitrogen (N) - 14
chlorine (Cl) - 35.5	oxygen (O) - 16
chromium (Cr) - 52	potassium (K) - 39
copper (Cu) - 63.5	sodium (Na) - 23
fluorine (F) - 19	sulfur (S) - 32
iron (Fe) - 56	

1. The molecular formula of potassium sulfide is K_2S. How many moles of potassium (K) and sulfur (S) are contained in one mole of potassium sulfide?

2. Calculate the mass of hydrogen peroxide (H_2O_2) in 1.5 moles of hydrogen peroxide.

3. Consider the reaction between magnesium chloride ($MgCl_2$) and hydrogen fluoride (HF) according to the equation:

$$MgCl_2 + 2HF \rightarrow MgF_2 + 2HCl$$

If 95 grams of $MgCl_2$ and 80 grams of HF are mixed together and allowed to react until no further reaction occurs, calculate the mass of magnesium fluoride (MgF_2) produced.

4. Calculate the number of moles of acetylene (C_2H_2) in 52 grams of acetylene.

5. Sodium chloride (NaCl) reacts with magnesium bromide ($MgBr_2$) according to the equation:

$$2NaCl + MgBr_2 \rightarrow 2NaBr + MgCl_2$$

Calculate the <u>number of moles of sodium bromide (NaBr)</u> produced by 6 moles of $MgBr_2$.

6. Calcium carbonate ($CaCO_3$) reacts with sodium chloride (NaCl) according to the equeation:

$$CaCO_3 + 2NaCl \rightarrow Na_2CO_3 + CaCl_2$$

Calculate the <u>mass of calcium chloride ($CaCl_2$)</u> produced by 58.5 grams of NaCl.

7. Calculate the <u>molar mass</u> of nitrogen dioxide (NO_2).

8. The reaction between copper (Cu) and hydrogen fluoride (HF) produces copper fluoride (CuF_2) and hydrogen gas (H_2):

$$Cu + 2HF \rightarrow CuF_2 + H_2$$

What <u>mass of H_2</u> would be produced if 6.4 grams of Cu reacted with 4 grams of HF to produce 10.2 grams of CuF_2?

9. Consider the reaction between hydrogen gas (H_2) and aluminum sulfide (Al_2S) according to the equation:

$$3H_2 + Al_2S_3 \rightarrow 2Al + 3H_2S$$

If 4 moles of H_2 and 4 moles of Al_2S_3 are mixed together and allowed to react until no further reaction occurs, calculate <u>the number of moles of hydrogen sulfide (H_2S) produced</u>.

10. Consider the reaction between aluminum (Al) and hydrogen fluoride (HF) according to the equation:

$$2Al + 6HF \rightarrow 2AlF_3 + 3H_2$$

If 8 moles of Al and 9 moles of HF are mixed together and allowed to react until no further reaction occurs, calculate <u>the number of moles of aluminum fluoride (AlF_3) produced</u>.

APPENDIX 6

ITEMS TESTING SKILLS 1 TO 9 CHEMISTRY POSTTEST, PARTS ONE AND TWO

	PART ONE	PART TWO
9. Mass to Mass (Excess)	03	03
8. Moles to Moles (Excess)	07	09
7. Mass to Mass B	04	06
6. Mass to Mass A	08	08
5. Moles to Moles	09	05
4. Moles to Mass	05	02
3. Mass to Moles	02	04
2. Molar Mass	06	07
1. Molecular Formula	01	01

APPENDIX 7

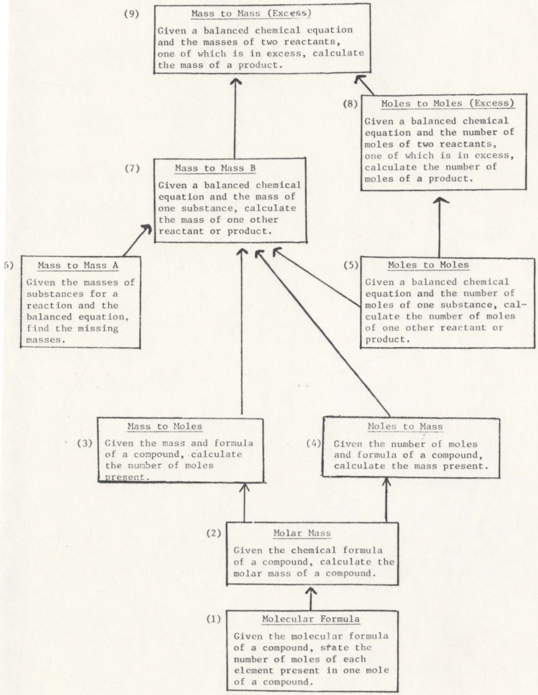
Name ______________________________

School ______________________________

Instructional Booklet

You have just recently completed a test on certain aspects of the MOLE. Your results indicated that you are having difficulty with some of the items. In order to correctly do any future work in chemistry you must first overcome these difficulties. If you do not they will prove to be a hinderance to your progress in this, and any future chemistry courses you may do. The material within this booklet, if covered properly by you, will help you to overcome these difficulties. You will only get out of it what you put into it!

The material covered in this instructional unit relates to the use of the mole concept in determining reacting weights of unknown substances. For further work in chemistry it is very important that you grasp this. The material is summarized in the chart below.



Each of the numbered blocks in the chart represents a chemistry skill with which you should be familiar.

The first half of the chart (Block Numbers 1, 2, 3 and 4) concentrates on compounds. Under this topic you will be concerned with doing various types of calculations based on compounds.

The second half of the chart (Block Numbers 5, 6, 7, 8 and 9) concentrates on the products of reaction between substances rather than on the substances themselves. Under this topic you will be concerned with doing calculations from chemical equations in terms of reactant or product, using either mass or mole quantities.

You have already dealt with these skills in class, and also written a test a short while ago based on them. Your results for the test indicated that you are having difficulty with some of the skills listed in the chart. This Instructional Booklet is intended to help you overcome these difficulties. As you aren't having difficulty with all of the skills in the chart it isn't necessary for you to cover all of the material in this booklet, instead just the material related to the skills you are having difficulty with.

The skills you had difficulty with are indicated below by a check (√) mark in front of those skills:

Key to Difficult Skills

For each of the skills you are having difficulty with, as indicated by the check marks (√) above, you are required to cover the material related to only these skills in this booklet. To do this systematically look up in the key the lowest numbered skill which has a check mark in front of it. It is the material related to this skill which you will have to cover first in this booklet. The page number next to the skill title tells you where the material related to the skill begins in this booklet. You are to turn to that page number and proceed through the material under the particular skill title. Once you have the material related to this skill completed, go to the next lowest numbered skill in the key having a check mark in front of it and do as you did for the previous skill. Continue doing this until you have covered all of the material related to the skills which have a check mark in front of them.

Calculations Based on Compounds

Molecular Formula - Skill 1

Skill Covered in Next Section	(2)	Given the chemical formula of a compound, calculate the molar mass of a compound.
		↑
Skill Covered in This Section	(1)	Given the molecular formula of a compound state the number of moles of each element present in one mole of a compound.

The molecular formula of a compound indicates the actual number of moles of each element present in one mole of the compound. Given the molecular formula for a compound, you should be able to state the number of moles of each element contained in one mole of the compound.

The molecular formula for hydrogen chloride is HCl. The symbols H and Cl indicate that hydrogen chloride is made from the elements hydrogen and chlorine. As this formula has no numbers written in the form of subscripts, one mole of hydrogen chloride must then contain one mole of hydrogen and one mole of chlorine atoms.

The molecular formula for sodium sulfide is Na_2S. It is made from the elements sodium (Na) and sulfur (S). The number "2", which is written as a subscript, indicates that one mole of sodium sulfide contains two moles of sodium. Also because there is no subscript (number) after the symbol for sulfur, one mole of sodium sulfide contains only one mole of sulfur.

The molecular formula for copper nitrate is $Cu(NO_3)_2$. The symbols indicate that it contains copper (Cu), nitrogen (N) and oxygen (O). The symbol for nitrogen and oxygen are in parentheses. To determine the number of moles of nitrogen and oxygen, multiply the subscript 2, by the number of moles of nitrogen and oxygen inside the parentheses. One mole of copper nitrate must then contain:

2 x 1 mole of N = 2 mole N

2 x 3 mole of O = 6 mole O

and only one mole of copper as Cu has no subscript behind it, and not being inside the parentheses, cannot be multiplied by the subscript 2.

The following steps can be used for stating the number of moles of each element, contained in one mole of a compound:

(1) Determine the elements in the compound from the symbols in the molecular formula.

(2)a Determine the number of moles of each element from the subscript immediately following the symbol for the element.

(2)b For symbols within parentheses the number of moles of each element is equal to the number of moles of the element (inside the parentheses) multiplied by the subscript (outside the parentheses).

Exercise

Complete these problems.

1. How many moles of each element are contained in one mole of each of the following:

   (a) lithium bromide, LiBr

   (b) carbon dioxide, CO_2

   (c) aluminum oxide, Al_2O_3

   (d) barium hydroxide, $Ba(OH)_2$

Turn to page 35 to check your answers.

<u>Instruction</u>

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest numbered skill which has a check mark in front of it. Then locate, across from this skill title the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Molar Mass - Skill 2

Skill Covered in Next Section	(3)	Given the mass and formula of a compound calculate the number of moles present.
Skill Covered in This Section	(2)	Given the chemical formula of a compound, calculate the molar mass of a compound.
Skill Covered in Last Section	(1)	Given the molecular formula of a compound state the number of moles of each element present in one mole of a compound.

The molar mass of a compound is the mass (number of grams) in one mole of the compound. You should be able to calculate the molar mass of a compound, given its molecular formula. To calculate the molar mass of a compound you have to know the number of moles of each element in one mole of the compound, and the molar mass of each element, obtainable from a periodic table.

The molecular formula for Lithium Sulfide is Li_2S. The molar mass of Li_2S is calculated by first finding the number of moles of each element in one mole of Li_2S. There are

2 mole Li / mole Li_2S

and 1 mole S / mole Li_2S

To find the molar mass, the number of moles of each element must be multiplied by their atomic masses and the individual masses added together. Doing this gives the following:

$$(2 \text{ moles} \times 7 \text{ grams/mole})\ Li\ /\ \text{mole}\ Li_2S$$
$$+\quad (1 \text{ mole} \times 32 \text{ grams/mole})\ S\ /\ \text{mole}\ Li_2S$$

which simplifies to:

$$(14 \text{ grams } Li + 32 \text{ grams } S)\ /\ \text{mole}\ Li_2S$$
$$\text{or}\quad 46 \text{ grams}\ /\ \text{mole}\ Li_2S$$

Therefore one mole of Li_2S has a mass of 46 grams.

The above could have been done using the following shorter method:

$$\begin{aligned} \text{Molar Mass } Li_2S &= (\ 2 \times \text{molar mass of Li}\ ) + \text{molar mass of S} \\ &= (\ 2 \times 7.0\ ) + 32.0 \\ &= 14 + 32 \end{aligned}$$

Therefore 1 mole of Li_2S = 46 grams

The following steps can be used for calculating the molar mass of a compound:

(1) Find the number of moles of each element in one mole of the compound.

(2) Multiply the number of moles of each element by the atomic mass of each element.

(3) Add together the individual masses obtained from step 2 together.

Exercise

Complete these problems:

2. Calculate the molar mass of one mole of each of the following:

   (a) magnesium chloride, $MgCl_2$

   (b) sodium sulfide, Na_2S

   (c) aluminum oxide, Al_2O_3

   (d) calcium nitrate, $Cu(NO_3)_2$

Turn to page 35 to check your answers.

Instruction

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest numbered skill which has a check mark in front of it. Then locate, across from this skill title the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Converting Mass to Moles - Skill 3

Skill Covered in Next Section	(4)	Given the number of moles and formula of a compound calculate the mass present.
		↑
Skill Covered in This Section	(3)	Given the mass and formula of a compound calculate the number of moles present.
		↑
Skill Covered in Last Section	(2)	Given the chemical formula of a compound, calculate the molar mass of a compound.

You should be able to convert a given mass of a compound to its corresponding number of moles. To do this you must know the molar mass of the compound.

Suppose you were asked to calculate the number of moles of Lithium Sulfide (Li_2S) contained in 92 grams of it. Earlier you calculated the molar mass of Li_2S to be 46 grams/moles (see page 9). To calculate the number of moles in 92 grams divide the molar mass into the given mass. This is done as shown below:

$$\frac{92 \text{ grams}}{46 \text{ grams/mole}} = 2 \text{ moles}$$

Therefore 92 grams of Li_2S is equal to two moles. Note that the units for the conversion from mass to moles are moles.

The following steps can be used for converting the mass of a compound to its number of moles:

(1) Calculate the molar mass of the compound (See page 9).

(2) Divide the molar mass into the mass of the compound.

Exercise

Complete these problems.

3. Calculate the number of moles of the named compound in each of the following masses:

   (a) 124 grams of sodium oxide, Na_2O

   (b) 17 grams of hydrogen sulfide, H_2S

Turn to page 35 to check your answers.

Instruction

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest numbered skill which has a check mark in front of it. Then locate, across from this skill title the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Converting Moles to Mass - Skill 4

Skill Covered in Next Section	(5)	Given a balanced chemical equation and the number of moles of one substance calculate the number of moles of one other reactant or product.
		↑
Skill Covered in This Section	(4)	Given the number of moles and formula of a compound calculate the mass present.
		↑
Skill Covered in Last Section	(3)	Given the mass and formula of a compound calculate the number of moles present.

You should be able to convert a given number of moles of a compound to its corresponding mass. To do this conversion you need to know the molar mass of the compound.

What mass of lithium sulfide (Li_2S) is contained in four moles of Li_2S? Earlier you determined that the molar mass of lithium sulfide was 46 grams/mole (see page 12). To calculate the mass in four moles, multiply the molar mass by the given number of moles. This is done as shown below:

$$4 \text{ moles} \times 46 \text{ grams/mole} = 184 \text{ grams}$$

Therefore four moles of lithium sulfide contains 184 grams.

The following steps can be used for converting the number of moles of a compound to its corresponding mass:

(1) Calculate the molar mass of the compound (See page 9).

(2) Multiply the number of moles of the compound by its molar mass.

Exercise

Complete these problems.

4. Calculate the mass of:

    (a) two moles of potassium oxide, K_2O

    (b) one-half (0.5) mole of propane, C_3H_8

Turn to page 35 to check your answers.

Instruction

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest numbered skill which has a check mark in front of it. Then locate, across from this skill title the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Calculations Based on Chemical Equations

The remainder of this booklet deals with a very important aspect of chemistry, that of being able to calculate the amount of one substance in a chemical reaction, given data for another substance. To do a calculation of this type requires the skills you had learned earlier in this booklet, and a balanced chemical equation.

Moles to Moles - Skill 5

Skill Covered in Next Section	(6)	Given the masses of substances for a reaction and the balanced equation find the missing masses.
		↑
Skill Covered in This Section	(5)	Given a balanced chemical equation and the number of moles of one substance calculate the number of moles of one other reactant or product.
		↑
Skill Covered in Last Section	(4)	Given the number of moles and formula of a compound calculate the mass present.

The first calculation of this type requires that you should be able to calculate the number of moles of one substance in a chemical reaction, given the number of moles of another substance, and a balanced chemical equation for the reaction.

An example of this type of problem and the procedure for working it out are given below.

<u>Problem</u>: Boron (B) reacts with hydrogen (HCl) to produce boron trichloride (BCl_3) and hydrogen gas (H_2) according to the equation:

$$2\ B + 6\ HCl \rightarrow 2\ BCl_3 + 3\ H_2$$

Calculate the number of moles of BCl_3 produced by 4 moles of Boron (B).

To calculate the answer you must first determine from the balanced equation the mole relationship between the number of moles of "known" substance (the substance whose quantity is given; B here) and the number of moles of "unknown" substance (the substance whose quantity is to be calculated; BCl_3 here). The mole relationship in this example is written as follows:

2 mole of B produces 2 mole of BCl_3

Note that in a mole relationship such as the one above

(1) the substances are represented by their chemical formula

(2) the number of moles of each substance is indicated by the number directly in front of the formula

(3) the "unknown" substance always goes at the end of the relationship regardless of which side of the equation it is found.

From the mole relationship you can determine the number of moles of BCl_3 produced by one mole of B, simply by dividing the number of moles of B into itself and the number of moles of BCl_3. Doing this to the above relationship gives

$$\frac{2}{2} \text{ mole of B produces } \frac{2}{2} \text{ mole of } BCl_3$$

which simplifies to

$$1 \text{ mole of B produces } 1 \text{ mole of } BCl_3$$

If you know the number of moles of BCl_3 produced by one mole of B, then to calculate the number of moles produced by four moles of B is only a matter of multiplying both quantities in the second relationship above by four. Doing this gives:

$$4 \times (1 \text{ mole of B produces } 1 \text{ mole of } BCl_3)$$

which works out to

$$4 \text{ mole of B produces } 4 \text{ mole of } BCl_3$$

This relationship shows that four moles of boron produces four moles of boron trichloride.

The following steps can be used for doing a "mole to mole" calculation such as the one above.

(1) Determine the relationship between the number of moles of "known" and "unknown" substances from the balanced chemical equation.

(2) Determine the number of moles of "unknown" substance corresponding to one mole of "known" substance.
(It may be necessary to divide each quantity in Step I by the number of moles of the "known" substance.)

(3) Determine the number of moles of "unknown" substance corresponding to the given number of moles of the "known" substance. (Multiply each quantity determined in Step 2 by the number of moles of known substance specified in the problem.)

Exercise

Complete these problems.

5. Aluminum oxide (Al_2O_3) reacts with carbon (C) to produce aluminum (Al) and carbon dioxide (CO_2) according to the equation:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

(a) Calculate the number of moles of Al produced by six moles of Al_2O_3.

(b) Calculate the number of moles of CO_2 produced by six moles of C.

Turn to page 35 to check your answers.

Instruction

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest numbered skill which has a check mark in front of it. Then locate, across from this skill title the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Mass to Mass (A) - Skill 6

Skill Covered in Next Section	(7)	Given a balanced chemical equation and the mass of one substance calculate the mass of one other reactant or product.
Skill Covered in This Section	(6)	Given the masses of substances for a reaction and the balanced equation find the missing masses.
Skill Covered in Last Section	(5)	Given a balanced chemical equation and the number of moles of one substance calculate the number of moles of one other reactant or product.

The second type of calculation requires that you should be able to calculate the mass (number of grams) of one substance in a chemical equation, given the mass of another substance, and a balanced chemical equation for the reaction.

To aid you in doing this, it should be first illustrated, by means of a simple equation that during any chemical reaction there is no detectable increase or decrease in the quantity of matter reacted or produced. This is a law of nature. If it were not true, we would not be able to write any balanced equations. If you ever find the total mass on each side of an equation to be unequal you have made a mistake.

Therefore you can conclude that mass is conserved during a chemical reaction.

Problem: The reaction between lithium chloride (LiCl) and hydrogen fluoride (HF) produces lithium fluoride (LiF) and hydrogen chloride (HCl):

$$LiCl + HF \rightarrow LiF + HCl$$

If 8.5 grams of LiCl reacts with 4 grams of HF to form 5.2 grams of LiF, what mass of hydrogen chloride (HCl) was produced?

If mass is conserved during this reaction, the total mass of reactants must equal the total mass of the products or,

MASS LiCl + MASS HF = MASS LiF + MASS HCl

Placing into the above equation the specified masses from the problem gives

8.5 grams of LiCl + 4 grams of HF = 5.2 grams of LiF + ? grams of HCl

which reduces to

12.5 grams of LiCl and HF = 5.2 grams of LiF + MASS HCl

In order for mass to be conserved in this reaction HCl must have a mass equal to 7.3 grams.

Then

8.5 grams of NaCl + 4 grams of HF = 5.2 grams of LiF + 7.3 grams of HCl

or

12.5 grams of LiCl and HF = 12.5 grams of LiCl and HCl

Therefore, 7.3 grams of hydrogen chloride must have been produced.

Exercises

Complete these problems.

6 (a) The reaction between lithium hydroxide (LiOH) and sodium chloride (NaCl) produces sodium hydroxide (NaOH) and lithium chloride (LiCl):

$$LiOH + NaCl \rightarrow LiCl + NaOH$$

What mass of NaOH would be produced if 4.8 grams of LiOH reacted with 11.7 grams of NaCl to produce 8.5 grams of LiCl?

(b) Water (H_2O) decomposes to form hydrogen gas (H_2) and oxygen gas (O_2) according to the equation

$$H_2O \rightarrow H_2 + \frac{1}{2} O_2$$

What mass of O_2 is formed if 9 grams of H_2O decomposed to form 1 gram of H_2?

Turn to page 35 to check your answers.

Instruction

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest numbered skill which has a check mark in front of it. Then locate, across from this skill title the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Mass to Mass (B) - Skill 7

Skill Covered in Next Section	(8)	Given a balanced chemical equation and the number of moles of two reactants, one of which is in excess calculate the number of moles of a product.
		↑
Skill Covered in This Section	(7)	Given a balanced chemical equation and the mass of one substance calculate the mass of one other reactant or product.
		↑
Skill Covered in Last Section	(6)	Given the masses of substances for a reaction and the balanced equation find the missing masses.

An example of the previous problem, now applied to a more complex one, is given below.

Problem: Nitrogen gas (N_2) reacts with water (H_2O) according to the equation:

$$2\ N_2 + 6\ H_2O \rightarrow 4\ NH_3 + 3\ O_2$$

What mass of ammonia (NH_3) would be produced from 14 grams of (N_2)?

The mass of N_2 (the known substance) must first be changed to its corresponding number of moles of N_2. Earlier in this booklet you learned this skill (see page 12). It required that the molar mass of the substance be divided into the given mass. As the molar mass of N_2 is 28 grams/mole, the number of moles corresponding to 14 grams of N_2 is

$$\frac{14 \text{ grams}}{28 \text{ grams/mole}} = 0.5 \text{ mole of } N_2$$

Calculating the number of moles of NH_3 (the unknown substance) produced by the 0.5 mole of N_2 is a "mole to mole" calculation, requiring you to use the three steps listed earlier for doing such a calculation (See page 12).

The first step required you to find the mole relationship between N_2 and NH_3. From the equation it is written as

2 mole N_2 produces 4 mole NH_3

The second step required you to calculate the number of moles of NH_3 produced by one mole of N_2. Dividing both quantities by 2 in the above relationship gives this, which is written as

1 mole N_2 produces 2 mole NH_3

The third step required you to calculate the number of moles of NH_3 produced by 0.5 mole of N_2. Multiplying the second mole relationship above by 0.5 gives this which is written as

0.5 mole N_2 produces 1 mole NH_3

To obtain the mass of NH_3 is only a matter of changing the 1 mole of NH_3 to its corresponding mass. Earlier in the booklet you learned this skill (see page 14). It required that the molar mass of the substance be multiplied by the specified number of moles. As the molar mass of NH_3 is 17 grams/mole, then the mass of one mole of NH_3 is

$$1 \text{ mole} \times 17 \text{ grams/mole} = 17 \text{ grams } NH_3$$

Therefore 17 grams of ammonia would be produced from 14 grams of nitrogen gas.

The following steps can be used for doing a "mass to mass" calculation such as the one above.

(1) Determine the number of moles of "known" substance.

(2) Determine the number of moles of "unknown" substance corresponding to the specified number of moles of "known" substance. (This step is done using the three steps listed earlier for the "mole to mole" calculation. See page 18).

(3) Determine the mass of the "unknown" substance.

Exercise

Complete these problems

7. Methane (CH_4) reacts with oxygen gas (O_2) according to the equation:

$$CH_4 + 2O_2 \rightarrow CO_2 \; 2H_2O$$

   (a) If 8 grams of CH_4 are reacted, what mass of water (H_2O) would be produced?

   (b) If 32 grams of O_2 are reacted, what mass of carbon dioxide (CO_2) would be produced?

Turn to page 35 to check your answers.

Instruction

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest skill which has a check mark in front of it. Then locate, across from the skill title the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Moves to Moles (Excess) - Skill 8

Skill Covered in Next Section	(9)	Given a balanced chemical equation and the masses of the reactants, one of which is in excess, calculate the mass of a product.
Skill Covered in This Section	(8)	Given a balanced chemical equation and the number of moles of two reactants, one of which is in excess, calculate the number of moles of a product.
Skill Covered in Last Section	(7)	Given a balanced chemical equation and the mass of one substance, calculate the mass of one other reactant or product.

The third type of calculation requires that you should be able to calculate the number of moles of a product, given the number of moles of two reactants, one of which is in excess, and a balanced chemical equation. This type of calculation is just an extension of the "Mole to Mole" calculation done earlier in this booklet. (See pages 16-19.

An example of this type of problem and the procedure for working it out are given below.

<u>Problem</u>: Consider the reaction between boron (B) and hydrogen chloride (HCl) according to the equation:

$$2\ B + 6\ HCl \rightarrow 2\ BCl_3 + 3\ H_2$$

If 4 moles of B and 18 moles of HCl are mixed together and allowed to react until no further reaction occurs, calculate the number of moles of boron trichloride (BCl_3) produced.

You must first determine the mole relationships between B and BCl_3 and between HCl and BCl_3. These two relationships will indicate the number of moles of BCl_3 (the unknown substance) produced by each of B and HCl (the known substances).

Earlier in the booklet, using the three steps listed for doing "mole to mole" calculations (see pages 16-19) it was decided that:

4 mole B produces 4 mole BCl_3

Using the same three steps it can be shown that:

18 mole HCl produces 6 mole BCl_3

These two relationships indicate that two possible amounts of BCl_3 can be produced. To decide which one of these two amounts will form you must decide which of B and HCl is the "Limiting Reagent". The "Limiting Reagent" is that reagent which limits the amount of product that can form. Therefore the:

<u>"Limiting Reagent" is the reagent that gives the least number of moles of the product.</u>

As Boron produces the least number of moles of BCl_3 it must be the "Limiting Reagent". Therefore 4 moles of boron and 18 moles of hydrogen chloride produced 4 moles of boron trichloride when the reaction was completed.

This implies that HCl was in excess. In other words, there wasn't enough Boron to react with all 18 moles of HCl. Boron then limited the amount of HCl that could react and therefore the amount of boron trichloride that could be produced.

The following steps can then be used for doing a "Mole to Mole - Excess" calculation such as the one above.

(1) Determine the number of moles of "unknown" substance corresponding to the specified number of moles of each "known" substance in the problem.

(2) Determine which reactant is the Limiting Reagent.

(3) Determine the number of moles of "unknown" substance which will be produced by the Limiting Reagent.

Exercise

Complete this problem.

8. Consider the reaction between aluminum oxide (Al_2O_3) and hydrogen gas (H_2) according to the equation:

$$Al_2O_3 + 3H_2 \rightarrow 2Al + 3H_2O$$

If two moles of Al_2O_3 and 7 moles of H_2 are mixed together and allowed to react until no further reaction occurs, calculate the number of moles of water (H_2O) produced.

Turn to page 35 to check your answers.

Instruction

Once you have completed the additional exercise turn back to the key on page 4. Find the next lowest numbered skill which has a check mark in front of it. Then locate, across from this skill title, the page number where the material related to this skill begins in the booklet. Turn to that page and proceed to complete the material under this skill title.

Mass to Mass (Excess) - Skill 9

Skill Covered in This Section	(9)	Given a balanced chemical equation and the masses of two reactants, one of which is in excess, calculate the mass of a product.
Skill Covered in Last Section	(8)	Given a balanced chemical equation and the number of moles of two reactants, one of which is in excess, calculate the number of moles of a product.

The fourth type of calculation requires that you should be able to calculate the mass of a product, given the masses of two reactants, one of which is in excess, and a balanced chemical equation. This type of calculation is just an extension of the "Mass to Mass" calculation done earlier in this booklet (see pages 23-26).

An example of this type of problem and the procedure for working it out are given below:

Problem: Consider the reaction between nitrogen gas (N_2) and water (H_2O) according to the equation:

$$2N_2 + 6\ H_2O \rightarrow NH_3 + 3\ O_2$$

If 14 grams of (N_2) and 36 grams of (H_2O) are mixed together and allowed to react until no further reaction occurs, calculate the mass of ammonia (NH_3) produced.

You must first convert the masses of N_2 and H_2O (the known substances) to their corresponding number of moles. Earlier in the booklet (see page it was determined, by dividing the molar mass of N_2 into the given mass of N_2 that 14 grams of N_2 was equal to 0.5 moles of N_2. Doing the same for H_2O shows that 36 grams of H_2O is equal to 2.0 moles.

Using the number of moles of N_2 and H_2O, you must determine the mole relationships between N_2 and NH_3, and between H_2O and NH_3. These two relationships will indicate the number of moles of NH_3 (the unknown substance) produced by each of N_2 and H_2O.

You should notice that this problem has now developed into a "Mole to Mole - Excess" calculation. Then to calculate the number of moles of NH_3 which will form is only a matter of following the three steps listed earlier for doing this type of problem (see page 24).

The first step requires that the number of moles of NH_3 that can be produced from each of N_2 and H_2O be determined. This is done using the three steps for a "mole to mole" calculation (see pages 18-19)

0.5 mole N_2 produces 1.00 mole NH_2

and

2.0 mole H_2O produces 1.33 mole NH_3

The second step requires that the Limiting Reagent be determined, by choosing the reagent that gives the least number of moles of a product. In this problem the Limiting Reagent is N_2, as it only produces 1.00 mole NH_3.

The third step requires that the Limiting Reagent be used to determine the moles of NH_3 produced. The relationship above indicates that 1.00 mole of NH_3 was produced.

To complete the calculation the number of moles of NH_3 must be converted to its corresponding mass. Earlier in the booklet this calculation was done (see page 25). It was found that one mole of NH_3 is equivalent to 17 grams.

Therefore 14 grams of nitrogen gas and 36 grams of water produced 17 grams of ammonia. This implies that the water must have been in excess.

The following steps can be used for doing a "Mass to Mass - Excess" calculation such as the one above.

(1) Determine the number of moles of each "known" substance.

(2) Determine the number of moles of "unknown" substance which would be produced by each of the "known" substances (see the "Mole to Mole - Excess" calculation on page 29 for an example of how this step is executed).

(3) Identify which reagent is the "Limiting Reagent" (see page 28).

(4) Determine the number of moles of "unknown" substance which would be produced by the "Limiting Reagent".

(5) Determine the mass of the "unknown" substance in step 4.

Exercise

Complete this problem.

9. Consider the reaction between calcium sulfide (CaS) and hydrogen chloride (HCl) according to the equation:

$$CaS + 2\ HCl \rightarrow CaCl_2 + H_2S$$

If 36 grams of CaS and 73 grams of HCl are mixed together and allowed to react until no further reaction occurs, calculate the mass of calcium chloride ($CaCl_2$) produced.

Turn to page 35 to check your answer.

Answers to Exercises at the End of Each Skill Section

1. (a) 1 mole Li
   1 mole Br
   (b) 1 mole C
   2 mole O
   (c) 2 mole Al
   3 mole O
   (d) 1 mole Ba
   2 x 1 = 2 mole O
   2 x 1 = 2 mole H Turn to page 36 and do Exercise #1
2. (a) 95.3 gram/mole
   (b) 78.1 gram/mole
   (c) 102 gram/mole
   (d) 187.5 gram/mole Turn to page 36 and do Exercise #2
3. (a) 2.0 mole Na_2O
   (b) 0.5 mole H_2S Turn to page 36 and do Exercise #3
4. (a) 188.4 grams K_2O
   (b) 22 grams C_3H_8 Turn to page 36 and do Exercise #4
5. (a) 12 mole Al
   (b) 6 mole CO_2 Turn to page 36 and do Exercise #5
6. (a) 8 grams NaOH
   (b) 8 grams O_2 Turn to page 37 and do Exercise #6
7. (a) 18 grams H_2O
   (b) 22 grams CO_2 Turn to page 37 and do Exercise #7
8. 6 mole H_2O Turn to page 37 and do Exercise #8
9. 55.5 grams $CaCl_2$ Turn to page 38 and do Exercise #9

Additional Exercise Section

Molecular Formula - Skill I

1. How many moles of each element are contained in one mole of sodium sulfate (Na_2SO_4)? (Turn to page 39 to check your answer.)

Molar Mass - Skill 2

2. Calculate the molar mass of one mole of calcium chloride ($CaCl_2$). (Turn to page 39 to check your answer.)

Converting Mass to Moles - Skill 3

3. Calculate the number of moles of hydrogen chloride (HCl) in 73 grams of it. (Turn to page 39 to check your answer.)

Converting Moles to Mass - Skill 4

4. Calculate the mass of two moles of sodium sulfate (Na_2SO_4). (Turn to page 39 to check your answer.)

Mole to Mole - Skill 5

5. Boron (B) reacts with hydrogen chloride (HCl) to produce boron trichloride (BCl_3) and hydrogen gas (H_2) according to the equation:

$$2B + 6HCl \rightarrow 2BCl_3 + 3H_2$$

Calculate the number of moles of H_2 produced by 3 moles of hydrogen chloride (HCl). (Turn to page 39 to check your answer.)

Mass to Mass - Skill 6

6. Silver (Ag) reacts with chlorine gas (Cl_2) to produce silver chloride (AgCl) according to the equation:

$$Ag + 2\ Cl_2 \rightarrow AgCl$$

What mass of AgCl was produced if 10.8 grams of Ag and 3.5 grams of Cl_2 were reacted? (Turn to page 39 to check your answer.)

Mass to Mass B - Skill 7

7. Nitrogen gas (N_2) reacts with water (H_2O) according to the equation:

$$2\ N_2 + 6\ H_2O \rightarrow 4NH_3 + 3O_2$$

What mass of oxygen gas (O_2) will be produced from 54 grams of H_2O? (Turn to page 39 to check your answer.)

Moles to Moles (Excess) - Skill 8

8. Consider the reaction between methane (CH_4) and oxygen gas (O_2) according to the equation:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

If 2 moles of CH_4 and 5 moles of O_2 are mixed together and allowed to react until no further reaction occurs calculate the number of moles of water (H_2O) produced. (Turn to page 39 to check your answer.)

Mass to Mass (Excess) - Skill 9

9. Consider the reaction between acetylene (C_2H_2) and oxygen gas (O_2) according to the equation:

$$2C_2H_2 + 5\ O_2 \rightarrow 4CO_2 + 2\ H_2O$$

If 13 grams of C_2H_2 and 64 grams of O_2 are mixed together and allowed to react until no further reaction occurs, calculate the number of grams of carbon dioxide (CO_2) produced. (Turn to page 39 to check your answer.)

Answers for the Additional Exercise Section

1.	2 mole Na 1 mole S 4 mole O	Return to page 8 and read the instruction.
2.	111.1 grams/mole	Return to page 11 and read the instruction.
3.	2 moles	Return to page 13 and read the instruction.
4.	284.2 grams	Return to page 15 and read the instruction.
5.	1.5 mole H_2	Return to page 19 and read the instruction.
6.	14.3 grams AgCl	Return to page 22 and read the instruction.
7.	48 grams O_2	Return to page 26 and read the instruction.
8.	4 mole H_2O	Return to page 30 and read the instruction.
9.	44 grams CO_2	

APPENDIX 8

TEST SCORES FOR SKILLS 1 TO 9 ON THE CHEMISTRY PRETEST AND CHEMISTRY POSTTEST

NOTE: Subjects whose responses were not clearly interpretable for any item on part one or two of the Chemistry Pretest or Chemistry Posttest were treated as missing data for analyses involving the particular test(s). Such subjects are represented by a "9" in Table 11. Subjects whose ID begins with a 1, 2 or 3 were administered parts one or two of the Chemistry Pretest and Chemistry Posttest in single period settings. Some of these subjects were absent for one part of the pretest or posttest or both. Such subjects were treated as missing data for the analyses involving the particular test(s) and are represented by and "8" in Table 11. Any other subject, who was absent from the administration of both parts of the Chemistry Pretest or Chemistry Posttest in a double period setting, is also represented by an "8" in Table 11, and also were treated as missing data for the analysis involving the particular test(s).

ID	Chemistry Pretest									Chemistry Posttest								
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718	0	0	0	0	0	2	2	2	1	0	2	0	2	2	2	2	2	2
719	0	0	0	0	2	2	2	2	0	2	2	2	2	2	2	2	2	2
720	2	2	2	2	2	2	1	2	0	2	2	2	2	2	2	2	2	2
721	0	0	2	1	2	2	2	2	1	2	2	2	2	2	2	2	2	2
722	0	0	1	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2
723	0	0	2	0	2	2	2	2	1	2	2	2	2	2	2	1	2	2

Continued

ID	Chemistry Pretest									Chemistry Posttest								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
724	0	0	2	0	2	2	1	2	2	0	0	2	2	0	2	2	2	0
725	0	0	0	0	0	0	2	2	2	0	2	0	2	0	1	2	2	2
726	0	1	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2
727	0	0	0	2	2	2	2	2	1	2	2	2	2	2	2	2	2	2
728	0	0	0	0	2	2	0	2	2	1	2	2	2	2	2	2	2	2
729	2	2	2	2	2	2	2	2	0	2	2	2	2	2	2	2	2	2
720	0	0	0	1	2	2	2	2	0	2	2	2	2	2	2	2	2	2
731	0	0	2	0	2	2	2	2	2	1	1	2	2	2	2	2	2	2
732	0	0	0	0	0	2	2	2	2	2	2	1	1	2	2	2	2	2
733	0	0	0	0	0	2	2	2	2	2	2	2	1	2	2	2	2	2
734	0	0	0	0	0	2	2	2	2	1	2	1	2	2	2	2	2	2
735	8	8	8	8	8	8	8	8	8	0	2	2	2	2	2	2	2	2
736	0	0	0	0	2	2	1	2	2	2	2	2	2	2	2	2	2	2
737	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
738	2	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
739	0	1	1	1	2	1	2	2	0	2	1	2	2	2	2	2	2	2
740	0	2	1	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2
741	1	1	2	2	2	2	2	2	1	1	2	2	2	2	2	2	2	2
742	1	2	2	2	2	2	2	2	0	1	2	2	2	2	2	2	2	2
743	8	8	8	8	8	8	8	8	8	2	2	2	2	2	2	2	2	2