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ABSTRACT

This booklet is a teacher's manual in a series of booklets that make up the core of a Physical Science course designed for the freshman year of college and used by teachers in the 27 colleges participating in the Thirteen College Curriculum Program. This program is a curriculum revision project in support of 13 predominantly Negro colleges and reflects educational research in the area of disadvantaged youth. This unit covers the fundamental principles of chemistry, including distinguishing features of four chemical classes of elements and patterns of chemical combinations of elements. Experiments are provided to illustrate the major concepts of chemical combination. (MLH)

CHEMISTRY

TEACHER'S CURRICULUM GUIDE

for the
Thirteen-College Curriculum Program

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The Institute for Services to Education was incorporated as a non-profit organization in 1965 and received a basic grant from the Carnegie Corporation of New York. The organization is founded on the principle that education today requires a fresh examination of what is worth teaching and how to teach it. ISE undertakes a variety of educational tasks, working cooperatively with other educational institutions, under grants from government agencies and private foundations. ISE is a catalyst for change. It does not just produce educational materials or techniques that are innovative; it develops, in cooperations with teachers and administrators, procedures for effective installation of successful materials and techniques in the colleges.

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In addition, Miss Patricia Parrish serves as general editor of the curriculum materials as well as an Administrative Assistant to the Director. Mrs. Joan Cooke is Secretary to the Director.

The curriculum staff is assisted in the generation of new educational ideas and teaching strategies by teachers in the participating colleges and outside consultants. Each of the curriculum areas has its own advisory committee, with members drawn from distinguished scholars in the field but outside the program.

The number of colleges participating in the program has grown from the original thirteen of 1967 to neneteen in 1970. The original thirteen colleges are:

Alabama A and M University	Huntsville, Alabama
Bennett College	Greensboro, North Carolina
Bishop College	Dallas, Texas
Clark College	Atlanta, Georgia
Florida A and M University	Tallahassee, Florida
Jackson State College	Jackson, Mississippi
Lincoln University	Lincoln University, Pennsylvania

Norfolk State College	Norfolk, Virginia
North Carolina A and T State University	Greensboro, North Carolina
Southern University	Baton Rouge, Louisiana
Talladega College	Talladega, Alabama
Tennessee State University	Nashville, Tennessee
Voorhees College	Denmark, South Carolina

A fourteenth college joined this consortium in 1968, although it is still called the Thirteen-College Consortium. The fourteenth member is

Mary Holmes Junior College	West Point, Mississippi

In 1971, five more colleges joined the effort although linking up as a separate consortium. The members of the Five-College Consortium are:

Elizabeth City State University	Elizabeth City, North Carolina
Langston University	Langston, Oklahoma
Southern University at Shreveport	Shreveport, Louisiana
Saint Augustine's College	Raleigh, North Carolina
Texas Southern University	Houston, Texas

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The Carnegie Corporation
The ESSO Foundation

Thirteen College Consortium
Physical Science Teachers

Alabama A & M:	Army Daniels	Army Daniels	Army Daniels	Army Daniels
Bennett:	Perry Mack	Perry Mack	Dorothy Harris	Dorothy Harris
Bishop:	Burtis Robinson	Burtis Robinson	Burtis Robinson	Burtis Robinson
Clark:	Arthur Hannah	Arthur Hannah	Arthur Hannah	Arthur Hannah
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Jackson State:	Dennis Holloway	Dennis Holloway	Dennis Holloway	Dennis Holloway
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Mary Holmes:	----------	Thomas Wirth	Thomas Wirth	William Royal
Norfolk State:	Melvin Smith	Melvin Smith	Leon Ragland	Leon Ragland
North Carolina State:	Curtis Higgenbotham	Vallie Guthrie	Vallie Guthrie	Vallie Guthrie
Southern:	Thomas Wirth	Charles Osborne	Charles Osborne	-----------
Talladega:	Harban Singh	Harban Singh	Aleyamma George	Aleyamma George
Tennessee State:	Berry Hempstead	Berry Hempstead	Wil Cumming	Wil Cumming
Voorhees:	Bernie Dingle	Bernie Dingle	Bernie Dingle	Donald Volz

Five College Consortium Physical Science Teachers

1970-71

Elizabeth City State College	Kumar Chatterjie
Langston University	Jimmie White
Saint Augustine's College	Ramesh Mathur
Southern University at Shreveport	Margaret Knighton
Texas Southern University	Edward Booker

PREFACE

This booklet is one of a series of seven that make up up the core of a course in Physical Science designed and used by teachers in the twenty-seven colleges participating in the Thirteen-College Curriculum Program.

The course has several unique features. Especially important is its balanced emphasis on effective teaching methodology and basic concepts in the physical sciences. The two are closely woven into the fabric of the course. Consequently, in order that a teacher gain maximum use of these materials which were designed especially for the TCCP course it is essential that he understands the purposes it was designed to serve and the style and techniques chosen to accomplish them.

Course Objectives

The basic goal of the course is to make clear the nature of science as an enterprise and illustrate by numerous examples how science really proceeds. Exercises are chosen according to their potential to bring students into working contact with the essential aspects of the scientific experience. In these experiences the students develop concrete ideas about the operational meaning of, and the association between observation, experiment, measurement, hypothesis, theory, the nature of evidence, test, modification, formulating questions, accuracy of language, the role and value of schematic language in general and mathematics as an appropriate language in particular, the role of the observer, prediction, and the residual mystery of unanswered questions.

Secondly we strive to develop an appreciation for the features of science that distinguishes it from the other major disciplines, namely, the ability to establish a clear and testible criterion for the value of concepts and the role of experimentation as the sole criterion for the scientific truth. "Facts" and theories are never presented without a description; at least, of the experiments which support them.

By the use of a judicious choice of problems in the course we seek to divulge the peculiar nature of physical science that distinguishes it from other sciences. The course stresses the use of mathematics as a major analytical tool and the use of numerical patterns to describe physical phenomena.

Finally we are concerned with developing an appreciation for the value of "rigor" as a quality measure of a scientific study. A natural part of this is an exposure to- the development of the analytical tools and skills to deal with-scientific problems.

Pedagogical Priorities

High on our list of priorities in the course is the requirement that a substantial amount of learning take place in the classroom. Attention is given to creating learning situations where students collect information firsthand, consider its implications, and draw conclusions all within the same class period. The classrooms learning experiences are constructed so that they closely approximate real life situations where one has to search for clues and insights from a variety of sources, from reference materials, the teacher, as well as other students. The student must acquire the habit of weighing carefully the value of the information obtained from each.

Because of the variety of learning styles among the students, a mechanism is established for generating a variety of models of information integration. By encouraging students to actively participate in classroom exercises and develop ideas from the evidence that is presented for class inspection, the students themselves provide a range of models of learners. Students are encouraged to seek information from one another and teach themselves while the teacher supervises. This setting generates a number of dramatic experiences in a process of vital intellectual interaction.

The role of the teacher in the classrooms described above differs from that in a more traditional lecture oriented classroom where he is the central figure in the classroom and the prime source of information. In the settings described above the teacher becomes a coordinator. It is his responsibility to assist the students in seeking information and judging the value of what they find. He asks students the questions he would ask himself when he is in search of answers to crucial questions,displays the criteria he uses to reach conclusions, and thus allows the students themselves to make the crucial steps in the learning process. In order to be effective in this role, a teacher must accept as legitimate a wider base of student experiences, priorities, intellectual styles, and range of abilities.

It has been our experience that if these things are given proper attention, students develop an attitude about learning, where the learner is active, aggressive, and effective.

The Scope and Structure of the Course

The course is based upon five topics:

1. The Nature of Physical Science
2. Light
3. Inorganic and Organic Chemistry
4. Conservation principles
5. Gas Laws and Kinetic Theory

Each unit is self-contained, starting with a fundamental concept and developing in a spiral fashion through a hierarchy of levels. Each level contains the development of at least one fundamental idea from empirical data obtained in the laboratory, the demonstration of the utility of the concept, and a natural termination point that permits a study to end at a variety of levels always with a sense of completion. By virtue of their self-containment, a given unit may be interchanged in a course sequence with almost any other; consequently, a teacher may construct his course around the sequence of units that best suits his own interests and the background of his students.

FORMAT OF THE UNIT

This booklet has been designed to serve as a guide to assist the teacher in creating a successful classroom in a laboratory oriented course. As such it contains a number of hints, suggestions, and procedual instructions. When questions are presented in the text as a part of the development of a concept, answers are also given. These special features of the unit are unique to the teacher's version and do not appear in the companion student workbook.

There is a basic uniformity to the structure of each chapter. Each chapter is built around experimental activities that are designed to develop one or more fundamental physical concepts. The structure of the chapters are usually divided into four parts. First, to set the stage,we suggest a discussion session with the class to examine their initial ideas and attitudes about the problem to be studied and to establish a base of reference with which to compare the ideas that are developed in the course of the investigation. Secondly, we move to establish the rationale for beginning a particular experiment - or set of experiments - and design the experiment. Thirdly, experiments are carried out, data gathered, and the search for physical patterns begins. Once these patterns are identified and a useful description is constructed we move to an examination of its applications and implications.

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PART I - THE MACROSCOPIC WORLD

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I. FUNDAMENTAL PRINCIPLES OF CHEMISTRY

A. INTRODUCTION

Perhaps the most fundamental law of chemistry is that which describes the combination pattern of chemical elements as they form compounds. It deserves a place of fundamental importance because it forms the basis for our understanding of chemical behavior that enables us to accurately predict the details of chemical change. It is the heart of the subject of chemistry. Historically, chemistry was born when scientists began to discover the chemical elements and sought to list the way they combined to form new substances. It thrived when it was discovered that there was a simple regular pattern that could be used to describe combination tendencies of elements.

Early scientists did not - and had no experimental basis to encourage them to - search for a more fundamental truth in whose terms the pattern could be explained. Their's was a macroscopic theory, built on an understanding of the world as it operates on a large, classical scale. The patterns of chemical combination along with the concept of atoms as the smallest indivisible parts of matter form the basis of our knowledge of matter and chemical change until the beginning of the 20th Century. Since the macroscopic theory was based on the atom and represented a description of the empirical evidence as to how they interacted to combine and form compounds, any more "fundamental" theory had to await additional experimental evidence to disclose the internal structure of the atom and the nature of a new physical law to explain its behavior. This evidence was accumulated in the laboratory of early twentieth century physicists. Their discoveries had the effect of displacing the theoretical origins of chemistry from the world of the atom to the sub-atomic world of the electron. The laws of chemical combination were then viewed as effects of more fundamental causes; they were interpreted as natural consequences of the electrical interaction between the constituent parts of atoms and the laws of quantum physics that they obey

Each of these approaches to chemistry has its own advantage. Because it is more fundamental, the microscopic theory covers a broader range of problems. For example, in addition to providing a more elemental basis for why chemical elements combine as they do, it also explains how they combine, i.e., the dynamics of chemical reactions. The more fundamental theory is, then, the theoretical wellspring of the subject. On the other hand, a macroscopic theory of chemistry provides us with simpler laws. They are easier to apply and they are more consistent with our everyday sense of reality or intuition. Even the modern chemist who is well grounded in the laws of quantum physics and intimately familiar with the ultimate causes of molecular composition, relies on 'macroscopic' statements of the general patterns of chemistry in his day to day practice. He returns to the fundamentals of the quantum model only when general macroscopic rules and his intuition fail him. As a rule of thumb, he too finds the macroscopic world more comfortable. Yet, when we turn to teach the beginning students a conflict arises. There is on the one hand, a desire to point out the broad features of the subject in terms that he finds most natural and appealing and a desire, on the other, to present the whole and rigorous truth. In our zest to expose him to the fundamentals, the triumphs, and the beauties of chemistry, we often respond like well intended though overly zealous parents, smothering him in a sea of complexities with which he is unfamiliar and unprepared to deal. Confused, he often loses sight of precisely what is fundamental and the ability to judge for himself the value of what we have tried to teach him. For example, it is not uncommon to begin the study of chemistry by introducing molecular models, mumble something about electrons p, s, and d-shells, announce the utility of a thing called valence, intone the rules, and finally, verify its validity by analyzing the chemical composition of well known molecules. This streamlines the coverage of a vast number of topics; but the coverage is brief and hardly of much value. Even if the mumbles are replaced with clearer enunciations and the quick shuffle with detailed expositions, the relative emphasis of ideas is especially inappropriate for a beginning science student. He is usually most unprepared to deal with the axiomatic basis of a rigorous treatment and he loses sight of the value of the structure as a whole.

For students newly introduced to the fundamentals of science in general, let alone the rigors of precise chemistry, it is imperative that students assimilate new ideas in as comfortable and familiar a framework as possible, which means,in terms of a macroscopic model. The macroscopic theory has the advantage that the whole of the study can be based on experimental evidence, easily understood and interpreted in terms of everyday experience. Moreover, because of the simplicity of the approach, it represents a rare and important opportunity. The value of the model may be clearly traced, and shown to depend on its utility, no more and no less.

Needless to say, we use the macroscopic theory as an introduction to chemistry in the first part of this unit. After the principles of chemistry have been developed on this level, we turn to the development of fundamentals of a microscopic model in part II; but, it is only when the macroscopic model proves inadequate, that we search for more fundamental and regular causes.

B. FORMAT

This chapter develops three major concepts:

(a) Chemical elements are the primary substances of which all other substances are composed. It also points out the value of the general concept of an 'elemental' substance, which is a recurring theme in science.

(b) A knowledge of the patterns of chemical combination of the elements is an essential ingredient to the theory of chemistry. It enables us to predict the possibility of the outcome of chemical reactions.

c) The property of chemical activity is an empirical measure of the relative combining tendencies of elements that are in the same chemical class. A knowledge of this property of chemical elements enables us to determine the probability of the outcome of chemical reactions.

Together these concepts form a minimal basis for a workable theory of chemistry in which we may accurately predict the outcome of a large class of chemical reactions.

In the remainder of this chapter each of these concepts is developed separately around specially designed laboratory activities. At the end of each activity a list of problems and additional activities is given so that students may test the value of the concepts, assess the depth of their understanding, and measure their progress.

C. ELEMENTAL SUBSTANCES

1. A Discussion

Open an informal discussion on the general properties and features of chemistry, encouraging students to explore their own ideas, experiences, expectations, and uncertainties about the subject. Use specific questions such as those listed below.

Questions:

(a) What is chemistry?

(b) With what types of problems does it deal?

(c) With what kinds of things is it concerned?

(d) What kinds of laws are constructed to serve its purpose? Give examples of laws of chemistry?

(e) How are these laws useful?

(f) How is the subject used to serve society.

These questions serve as a background against which we may shape an appraisal of the major concepts outlined in section B.

2. An Activity

As the discussion develops, it is useful to appeal to analogies in fields other than chemistry, making comparisons with problems with which the students are more familiar. For example, a very fertile context within which we may develop the concept of 'elemental' substances, is in a study of colors. Below we have outlined an empirical investigation of a study of 'the theory of color' combination. It is pregnant with useful analogies. Several questions naturally occur that have useful parallels in chemistry.

In the study we review, what is meant by an 'elemental' or primary color and then explore its value in a 'theory of color'. We are able to measure its usefulness by defining the kinds of problems it enables us to solve that we could not have analyzed otherwise. In so doing we are able to demonstrate the value of the structure of a theory based on 'elemental' substances. In addition, in a more general vein, the study is an opportunity to underscore the advantages of the use of logic and the methods of mathematical analysis, including the language of equations, in solving problems in a traditionally 'un-mathematical' subject.

Theory of Color Combination

Equipment

Supply groups of students with water color paint boxes. The boxes should be prepared to contain only the colors, red, yellow, blue, green, orange, purple and brown.

Basis for a Theory:

An 'elemental' or primary color is one that cannot be created by mixing other colors. A minimum requirement for a theory of color is the identification of all of the 'elemental' colors and the cataloguing of the composition of all non-basic colors. Our project is to experimentally construct such a theory.

By a discussion with the class it is easily agreed that there are only seven distinct colors. All others are a mixture of these. Aqua-marine, for example, is not a distinct color because one would describe it as a "greenish"-blue. Moreover, we must agree that black and whiee are not basic colors. When added to a color; they only change the shade. Consequently, we will restrict our consideration to the above seven colors.

Teachers Note: All instructions and problems listed below are to be given to the student with the words underlined omitted. These are the answers to the implied questions.

Instruction I

Using the above definition of 'elemental' color, experimentally identify the primary colors as:

(I) Red, Yellow, and Blue and the secondary colors

(II) Orange, Green, Purple, and Brown.

The composition of the secondary colors are:

(III) Orange = Red + Yellow

(IV) Green = Yellow + Blue

(V) Purple = Red + Blue

(VI) Brown = Red + Blue + Yellow

These facts are the basis of a "fundamental" theory of color. As innocent as it may seem, coupled with the use of logic, they are powerful. For example, with them we can predict the results of combining any colors.

Application of the Theory of Color

Problems Set I - "Mixing Secondary Colors"

Identify the results of the following combination of secondary colors.

(1) Purple + Yellow $\overset{?}{=}$ Brown

(2) Red + Green $\overset{?}{=}$ Brown

Analysis

(1) as Purple = Red + Blue: from equation V

and

Red + Blue + Yellow = Brown: from equation VI

then

Purple + Yellow = Brown

(2) as Green = Blue + Yellow: from equation IV

and

Blue + Yellow + Red = Brown: from equation VI

then

Green + Red = Brown

Problem Set II - "Dissonant Colors"

There is a rule of thumb in painting that certain colors complement one another while others clash. For example, red and green are "clashing" colors, while red and yellow or blue and yellow are complementary. It turns out that one may generalize this result as follows: "Two colors that add to form brown are not pleasant visually when juxtaposed". Let us call these colors a "dissonant pair". Red and green, then, are a dissonant pair. How many other dissonant pairs can you find? Prove your result experimentally.

Analysis

Red + Blue = Purple: from equation V

then Purple and Yellow are dissonant pairs

as, (Red + Yellow) + Blue = Brown

Red + Yellow = Orange: from equation III

then

Orange and Blue are dissonant pairs

as

(Yellow + Blue) + Red = Brown

Yellow + Blue = Green: from equation IV

Green and Red are dissonant pairs.

Problem Set III - "A Question of Proportions"

One of the advantages of a clear statement of the fundamentals of a theory is that these experimental facts may be combined with logical reasoning, leading to conclusions that we could not ordinarily anticipate. The problems listed above and their analyses illustrate this.

Another advantage is that by examining combinations of facts plus the poor use of logic sometimes reveals the value of a concept that we take for granted. The misuse of the logic often produces an erroneous result that has a dramatic impact. Often it forces us to reassess our initial premises, with the result that we gain a new insight. For example, ask the students to inspect the following piece of 'mis-logic' and identify the error in reasoning.

"Purple and Green are the Same Colors"

Proof

Part A

As Red + Yellow = Orange

As Red + Blue = Purple

then Purple + Orange = Red + Yellow + Blue

but a

Red = Yellow + Blue = Brown

the

Purple + Orange = Brown

Part B

As Yellow + Blue = Green

and

Red + Yellow = Orange

then

Orange + Green + Red + Blue + Yellow

hence

Orange + Green = Brown

Conclusion;

As Purple + Orange = Brown

and

Green + Orange = Brown

then

Purple + Orange = Green + Orange

thus

Purple = Green

and <u>Purple and Green are the same colors</u>

Analysis

This problem contains a new feature, namely, it reveals a need to consider the proportions in which colors are combined. The error in the above analysis lies in the mishandling of the effects of these proportions. The correct analysis is as follows:

Orange + Purple

= Red = Yellow + Red + Blue

= 2parts Red + 1 part Yellow + 1 part Blue

= Red + Brown

+ "Reddish Brown"

while

Orange + Green

= Red + Yellow + Yellow + Blue

= Yellow + Brown

= "Yellowish Brown"

hence

Orange + Green ≠ Orange + Purple

then

Green ≠ Purple.

The problem emphasizes the importance of proportions in which 'elemental' colors are mixed to form new colors. In the original statement of the law, little consideration was given to the question of proportions as we were more concerned with general overall patterns. The implication in the statement, however, was that one mixes the colors in a one-to-one ratio. This problem warns us to be aware of that implicit consideration.

3. Researching the Literature

The study of color is a preparation for making many useful and suggestive comparisons with the characteristics of chemistry. In order to complete the basis for the comparison we must accumulate similar information about the subject of chemistry. On such fundamental points as the definition of elements, compounds and clarifying what is meant by a chemical combination of elements, we may profit by the experience of others and by reading appropriate accounts in textbooks and scientific articles. Very readable accounts of the fundamentals of chemistry may be found in the references cited below.

(a) A Short History of Chemistry (An Introduction to the Ideas on Concepts of Chemistry) by Isaac Asimov, published by Anchor Book, Doubleday & Co., Inc.

p. 8 14: An account of the Greek concept of elemental substances.

p. 15 - 28: An account of Alchemy, the pre-scientific of the chemistry.

p. 41 - 43: A description of the discoveries that led to a new view of elemental substances that laid the basis for chemistry as a science.

p. 70 - 89: A discussion of compounds and Dalton's Law of Multiple Proportions.

(b) Matter

One of the Life-Time Magazine Science Series books.

p. 9 - 12: An introduction to the concept of chemical elements.

p. 12 - 28: A description of the practice of Alchemy.

p. 34 -38: A discussion of compounds and Dalton's Law of Multiple Proportions.

(c) General Chemistry by Nebergall, Schmidt, and Holtzclaw,

4. Application of Fundamental Concepts of Problems:

In the following section we have listed several problems to demonstrate the value of the fundamental concepts of chemistry described in the reading assignments. These are important concepts on which the remainder of the chapter builds. In our treatment of the fundamental laws of chemistry we shall assume these concepts are well understood. These problems may be profitably pursued as homework or class projects. If students find some of them too difficult to work alone, it would be advisable to assign the problem as group homework problems.

One of the concepts implicitly relied on in most of these problems but not mentioned above, is that of the law of conservation of mass in a chemical reaction. Discuss this before assigning any problems.

As an aid to measuring a student's level of achievement in solving these problems, we have assigned each of them a degree of difficulty indicated by the number of stars preceding the problem number. One star problems are of average difficulty; two star problems are of more than average difficulty; and three star problems are the highest level of challenge.

published by Raytheon Education Co., Boston, 3rd edition.

p. 1 - 6: An introduction to all the basic concepts of Chemistry, elements, compounds, and the Law of Multiple Proportions.

This is a traditional general chemistry textbook. Any number of other basic texts will serve instead.

Divide the class into three groups and assign one of each to read one of the references cited above in preparation for a discussion during the next class period. Ask each student to be prepared to define and discuss the basic concepts of chemical compounds, and Dalton's Law of Multiple Proportions and make a comparison with their study of color.

Problem Set I - "Chemical Elements, Compounds, and Chemical Change"

The problems listed below may be answered using only the concepts developed in the preceding sections of this chapter, namely that of chemical elements, compounds, and the law of conservation of mass in chemical reactions.

*1. Construct an argument explaining why it is possible or impossible - i.e. inconsistent with the laws of chemistry - to invent a pill that when dissolved in a gallon of water turns the water plus the "stuff" in the pill into gasoline by a chemical reaction. It is not necessary to know the details of the reaction.

Note: Gasoline is an organic compound composed solely of hydrogen and carbon.

*2. Imagine you are a U. S. Senator on the sub-committee for the preservation and enhancement of vital natural resources. One of the important concerns of that committee would be our diminishing supply of gasoline. Suppose that a fellow senator proposes a bill to make federal funds available for fundamental research in chemical processes to turn sea water and other substances (as of yet not known) into pure gasoline with no waste.

(a) What scientific argument could you present in support of or against the value of his proposal?

(b) If you feel his proposal is unsound, is there an ammendment that you could make to make it scientifically sound?

**3. Analyze the validity of each of the following statements:

(a) One cannot make hydrogen by mixing chemical compounds and have something left over.

(b) One cannot make hydrogen by mixing compounds and have nothing left over.

(c) One cannot make hydrogen by mixing other elements (excluding hydrogen) and have something left over.

(d) One cannot make hydrogen by mixing other elements (excluding hydrogen) and have nothing left over.

(e) It is impossible under any circumstances using chemical processes to build a "hydrogen production" factory.

For the purposes of this problem assume that the only compound that hydrogen and water form together is water, H_2O. Water can be created chemically by combining the correct volumes of gases of its constituent elements. Suppose such a process is carried out, using the information below and identify the excess gases if any:

*4. 10 c.c. of H and 10 c.c. of O

*5. 10 c.c. of H and 5 c.c. of O

*6. 5 c.c. of H and 10 c.c. of O

*7. 5 c.c. of H and 5 c.c. of O

The properties of chemical change:

Below we have listed several suggested chemical changes in schematic form. Indicate which of these are not possible and state which laws of chemistry they violate.

In order to simplify the statement of the problems and to facilitate their analysis we have introduced a symbolic notation where:

E_1 represents some element labeled #1

E_2 represents a different element labeled #2

E_3 represents still a different element labeled #3

(E_1, E_2) represents a compound composed of elements E_1 and E_2.

(E_1, E_2) and E_3 represent a mixture of compound (E_1, E_2) and element E_3.

The arrow "$\Longrightarrow$" indicates a chemical change

Suggested changes.

**8. E_1 and E_2 $\Longrightarrow$ E_3

**9. E_1 and E_2 $\Longrightarrow$ (E_1, E_2)

**10. (E_1, E_2) and E_3 $\Longrightarrow$ E_4

**11. (E_1, E_4) and (E_2, E_3) $\Longrightarrow$ (E_1, E_3) and (E_2, E_4)

**12. (E_1, E_2) and (E_2, E_3) $\Longrightarrow$ (E_1, E_3) and E_3

D. The Patterns of Chemical Combination of Elements

The preceding sections of this chapter make clear the value of cataloguing the combination patterns of basic colors to form new colors and suggests the same method of investigation may be useful in a study of chemistry. It would be ideal to proceed to investigate the patterns of combination of the chemical elements by mixing them in the laboratory. Unfortunately, to do so would be dangerous, expensive, and extremely time consuming. A great deal of technical knowledge would be required to carry out the necessary experiments. We may however, simulate the experience by using computing devices that imitate the patterns. Students may then carry out their own investigation with speed, accuracy, and safety.

The purpose of this exercise, then, is to accumulate empirical evidence of the patterns of chemical combination of the elements. With these results we will begin to build a theory of chemistry.

1. The Experiment: Part I

Equipment:

Organize the students into investigation teams. Assign each group a Compound Detector and instruct them in this use. See Appendix I. These instruments have been constructed to contain information about only 25 elements.

As the first step in the study, instruct the students to search for compounds containing only two elements in a one-to-one ratio. More complex compounds will be considered later. The restriction is made at this point only to simplify the search.

Assign each group at least four different elements whose combination properties they are responsible for researching. Distribute the assignments so that the class as a whole will be researching when all groups have completed their research, the teacher acts as a research co-ordinator and collects the results, listing them on the board. In figure 1, we have listed the combination properties of the elements.

2. Analysis:

Instruct students to identify as many patterns of regularity in the data as they can. This is no easy task, for the preponderance of data is almost overwhelming. There are many ways to extract the principles of chemistry from them. The possibilities are so numerous that we cannot anticipate them all. A great deal depends on the students' backgrounds and their individual insights. As a guide to the teacher in shaping this study we outline the important features of these data below and develop the concepts that may be drawn from them. We also indicate the crucial stages of the development as we go along.

It must be borne in mind that the laws that we derive in this manner are not in themselves the prime object of this study. It is of equal importance that the students develop a sense of the process leading to their discovery and to measure the value of a law by its utility.

Data Patterns for Elements Combining in a One-to-One Ratio

The two most apparent features of the data are:

(a) Some elements, namely, He, Ne, and Ar do not combine with other elements. Thus, we may ignore them for the remainder of this section.

EMPIRICAL DATA ON COMBINATION PATTERNS OF ELEMENTS

P	B
P	Al
P	Ga

Ar: Nothing

Be	O
Be	S
Be	Se

Br	H
Br	Li
Br	Na

C	Si
C	Pb

Ca	Se
Ca	S
Ca	O

Cl	Li
Cl	H
Cl	Na

F	Na
F	H
F	Li

B	P
B	N
B	As

H	F
H	Br
H	Cl

He: Nothing

Li	Br
Li	F
Li	Cl

Mg	O
Mg	Se
Mg	S

N	Al
N	B
N	Ga

Na	F
Na	Cl
Na	Br

Ne: Nothing

Al	N
Al	P
Al	As

O	Be
O	Ca
O	Mg

As	Ga
As	B
As	Al

Pb	C
Pb	Si

Ga	As
Ga	N
Ga	P

S	Be
S	Mg
S	Ca

Se	Ca
Se	Mg
Se	Be

Si	C
Si	Pb

figure 1

(b) All the elements (save C, Si, and Pb) combine with the same number of elements, specifically three, while the exceptions C, Si, and Pb combine with only two.

(c) C, Si, and Pb combine only with one another.

The particular number, three, that characterizes the number of compounds that most of the elements form is a result of an arbitrary design feature of the compound detector and has no significance. What is important however, is the sameness of the number of compounds formed by each element. There is even a regularity in the number of compounds that the exceptions C, Si, and Pb form. This is a feature of the periodic recurrence of properties of the elements as we go through their list. However, we will make little use of it in the immediate study.

Chemical Classes

The most important and useful feature of these data is not apparent at first sight. It is the pattern leading to the concept of chemical classes. We may begin by noting that:

(d) This list of compounds may be divided into four self contained groups, each group containing information about how the elements within that group combine with one another. Each element appears only within one group. The number of elements is the same for three of these groups, while the fourth is different, containing only C, Si, and Pb.

This is a rather lengthy and some what involved statement of a rather simple pattern of arrangement more easily indicated schematically is figure 2. The fact that the data may be divided into four groups, three of

GROUP COMBINING ELEMENTS INTO SELF CONTAINED GROUPS

Group I

Br	H
Br	Li
Br	Na

Cl	Li
Cl	H
Cl	Na

F	Na
F	H
F	Li

H	F
H	Br
H	Cl

Li	Br
Li	F
Li	Cl

Na	F
Na	Cl
Na	Br

Group II

P	B
P	Al
P	Ga

B	P
B	N
B	As

N	Al
N	B
N	Ga

Al	N
Al	P
Al	As

As	Ga
As	B
As	Al

Ga	As
Ga	N
Ga	P

Group III

Be	O
Be	S
Be	Se

Ca	Se
Ca	S
Ca	O

Mg	O
Mg	Se
Mg	S

O	Be
O	Ca
O	Mg

S	Be
S	Mg
S	Ca

Se	Ca
Se	Mg
Se	Be

Group IV

C	Si
C	Pb

Pb	C
Pb	Si

Si	C
Si	Pb

figure 2

which have identical numbers is useful in reducing the number of data that we have to inspect in our search for a pattern. For example, if we assume that each of the three groups may have the same general properties, i.e. patterns, we may restrict our attention to only one of these. A closer inspection of one of these groups reveals that:

> (e) We have a duplication of information, as half of the description of the compounds contains the same information as the other half only listing the elements of the compounds in reverse order. Thus, we may omit the redundant half of these data.

This is a simple result and could have been obtained earlier. The more important advantage of this grouping is that there are sub-groups of three within the major group. Whenever a series of elements is found to combine with a given element, the same series of elements is found when one of them combines with some other element. For example, F, Br, and Cl in group I is such a series. H is found to combine with F, Br, and Cl; similarly Na is found to combine with F, Br, and Cl also; and Li is found to combine with the same set. It is convenient, then, to define series of such elements as forming a 'class'. The definition allows us an economy of language when describing the above combinations, for, whatever be the elements, one member of a class combines with them and no others. Similarly, H, Na, and Li form a chemical class.

This concept has the further advantage of further notational economy. We may denote the whole of the information contained in group I, of figure II by the simple equation:

$$\underset{\text{Class}}{\begin{pmatrix} \mathrm{H} \\ \mathrm{Na} \\ \mathrm{Li} \end{pmatrix}} \quad \underset{\text{Class}}{\begin{pmatrix} \mathrm{F} \\ \mathrm{Cl} \\ \mathrm{Br} \end{pmatrix}}$$

The implication of this notation is that every member of the class of elements on the left forms a compound with each of the elements in the class on the right. Hence, we have represented 9 compounds in one fel swoop.

We extend this notation to represent all of our experimental results in figure 3.

Using the Concept of Chemical Classes to Find Additional Regularities

Pursuing an analysis of our results a step further it becomes clear that:

(f) elements in the same class do not combine with one another to form compounds.

Although it may seem a trivial statement it is a great time saver. This result warns us that if we find H combines with element F and Na also combines with element F, that Na and H are in the same class therefore H does not combine with Na.

In studying our progress in cataloguing the patterns so far, it is a bit disconcerting that we have to make exceptions to our rules of chemical behavior for the three elements C, Si and Pb. We have developed rules and a notation that is very concise but cannot be applied to these three 'anomolous' elements. It would be very convenient if we did have to make an exception. For one thing it would make shorter work of our description of the overall pattern. Below we consider extending the method of classes to a description

DEVELOPMENT OF THE NOTATION TO REPRESENT CHEMICAL CLASSES

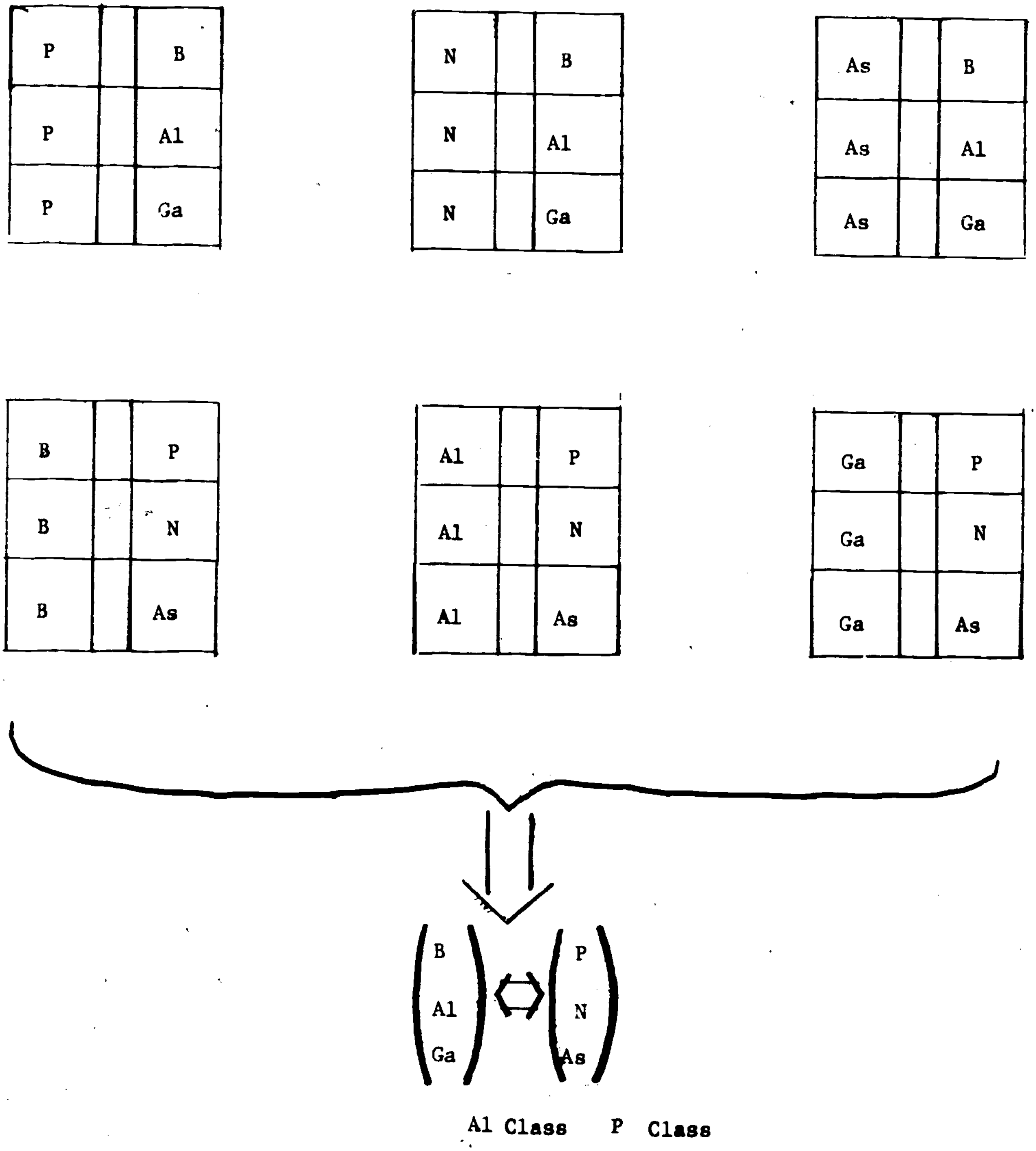

figure 3

A REPRESENTATION OF THE EMPIRICAL COMBINATION PATTERN USING CHEMICAL CLASSES

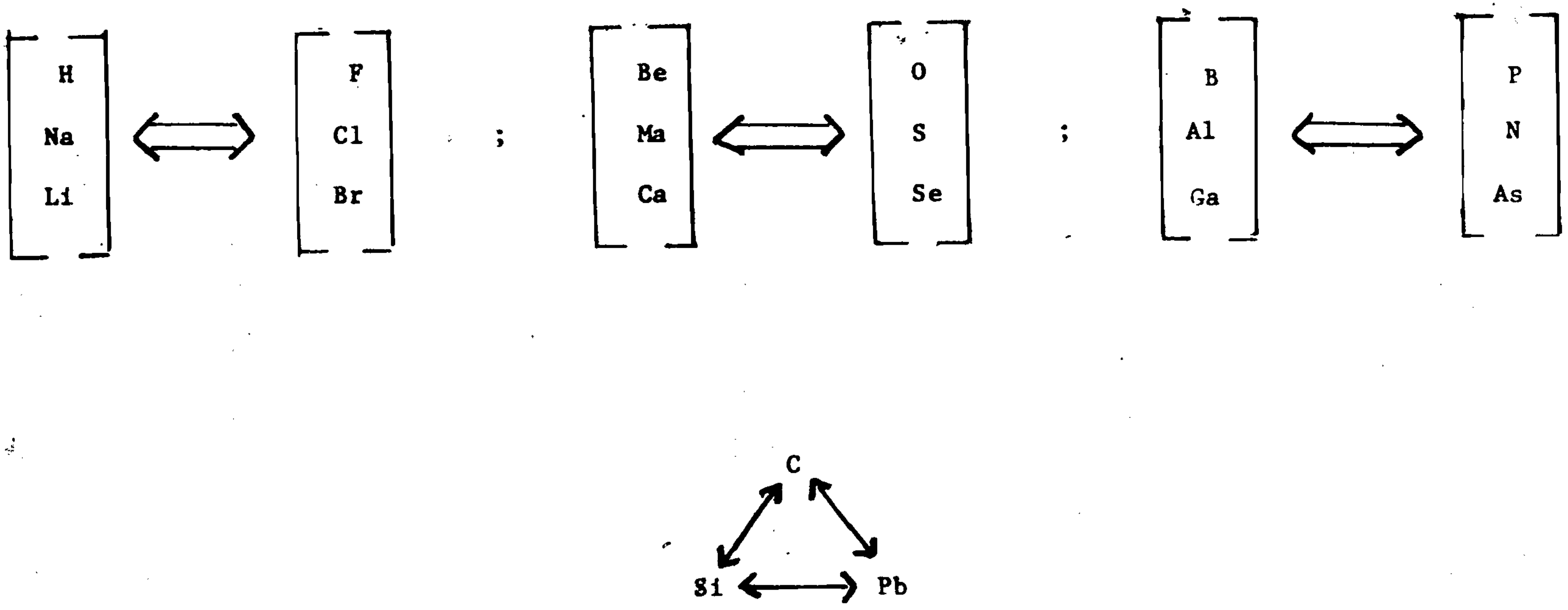

figure 4

of the behavior of these elements as well.

One of the regularities apparent in the properties of C, Si, and Pb is that there are only two elements with which each combines instead of three, as with the other elements. If, on the other hand, each of the elements C, Si, and Pb formed a 'compound' with itself, the schematic representation of their properties would fall in line with that for all the other elements.

Problem :

1. Show that if in addition to the information gathered above if C, Si, and Pb formed compounds with themselves, they form a chemical class.
2. Using the compound detector establish whether or not these elements form compounds with themselves.
3. Check whether any other elements have this property.

An experimental check indicates that their elements do in fact form compounds with themselves. And we may define their elements as forming a class which combines with an identical class. They are, however, still unique, for no other elements display this property.

Thus, our initial classification has led us to new insights and the whole of our experimental results is simply represented as in figure 5. The results of this 'triumph' also indicate that there is something special, perhaps more profound, about the notion of chemical class than we had first imagined. It has led us to a result that we could not have guessed.

Differences within Chemical Classes

Another way of defining the relationship between two elements in the

A REPRESENTATION OF THE EMPIRICAL COMBINATION PATTERN USING CHEMICAL CLASSES

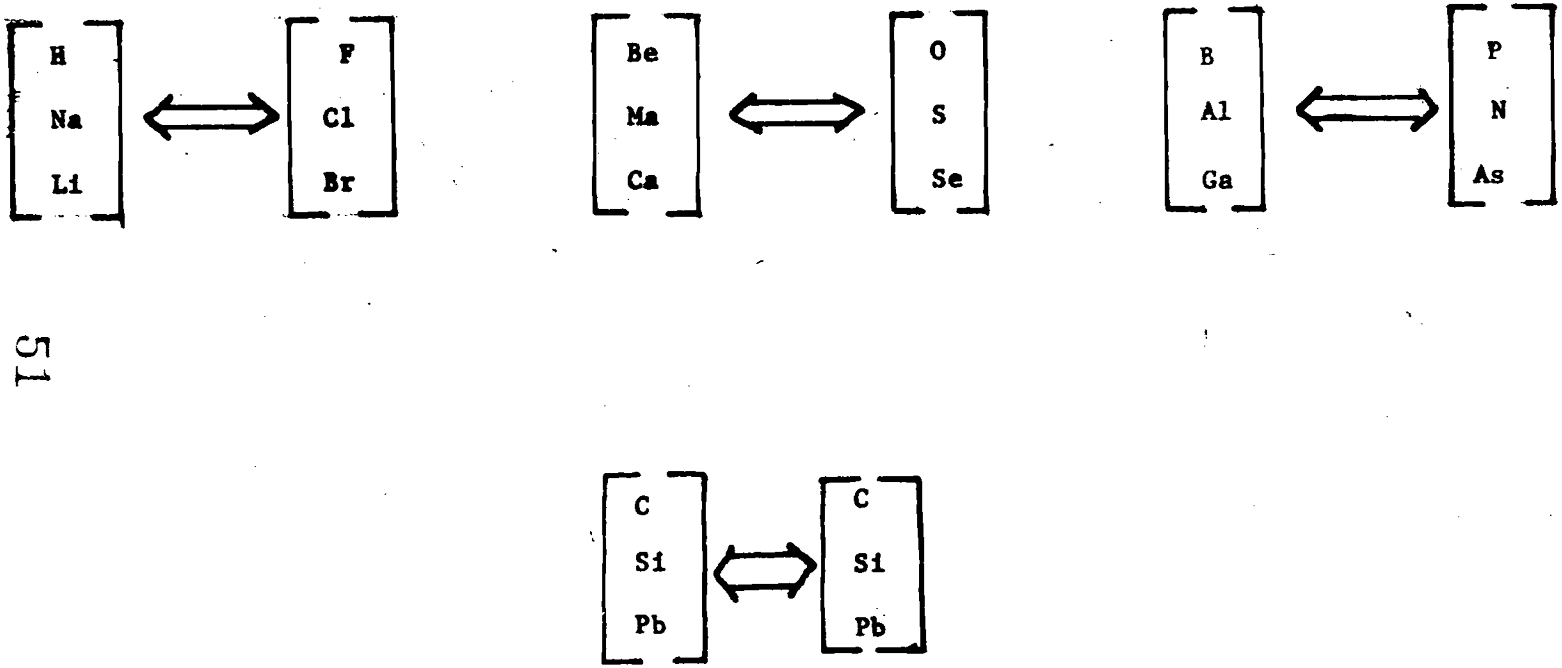

figure 5

same chemical class is to say that they display the same chemical behavior. A very simple explanation for this - although we have not as of yet begun to search for explanations of any of these analogous chemical phenomena - would be that, all elements in the same chemical class were as a matter of fact the same. The fact that they have different labels would simply be a case of 'mistaken identity'.

In the next section of this chapter we will develop the property of chemical activity to illustrate that there are also chemical differences between elements in the same class. But these differences represent properties that are of a finer grain than our simple computer is capable of reducing. It must be borne in mind that the purpose of this section is to point out that there are broad features in the chemical properties of the elements. Chemical differences within a class is a finer detail which will be considered in the next section.

PROBLEMS SET II: CHEMICAL CLASSES

*1. Suppose a friend of yours has just completed a study of the combination pattern of elements. One set of data he has collected is shown below.

Compounds Discovered:

H + F	Na + F
H + Br	Na + Br
H + I	Na + O
H + Cl	Na + Ca
But H combines with no other element	But Na combines with no other elements

Use the general properties you found in your experiment to explain why his data could not be correct.

*2. Arrange the elements in the compounds below in like chemical classes. Then use this information to predict other one-to-one ratio compounds that may be formed using the same elements.

HCl	MgS
NaF	CaS
MgO	MgSe
HF	

*3. Suppose that you had experimentally verified that the compounds listed above in problem 2 were valid. Using this information plus the concept of chemical class, prove or disprove the validity of the compounds postulated below.

HNa	ClF	CaO	HS
SS	SO	CaSe	CaCl
HMg	MgF	SeS	MgCl
NaH	NaCl	HH	HO

**4. Suppose the same friend who asked you to help him analyze his data in problem #1, has done another set of experiments and requests your help again. But this time he wants to be sure that you are <u>analyzing</u> his results and not just comparing them directly with your own results. Consequently, he hides the name of one of the elements from you, simply calling it compound X.

Using the principles of chemistry you have learned to analyze the validity of his results.

compounds discovered

HH	X-F
HFl	X-Br
HBr	X-O
HI	X-Ca
HCl	X-H
but H combines with no other element	but X combines with no other element

3. Review

At the conclusion of this part of the experiment we have discovered among the twenty-five elements studied, all possible combinations of elements that combine in pairs of two. We have done a complete study of the restricted problem defined at the beginning of section D. The results indicate a regular trend and we have discovered a natural grouping scheme that reflects it. Our discovery also shows signs of being of more general use than simply as an economical accounting scheme. It may contain the seeds of a more profound concept. But if we are to learn more about the patterns of compound formation, we will have to extend our study to cover a search for more complicated compounds.

Where do we go from here? Haven't we considered how all combine with one another? On the contrary, it is important to recognize how limited our study has been so far and how many more possibilities there are to consider. So far we have studied only how two elements combine, and even for these, only in a one-to-one ratio. For example, our study thus far indicates that hydrogen does not combine with oxygen. However, further study will show that hydrogen and oxygen do combine in a two-to-one ratio to form the well known and very common compound, water or H_2O. Our problem then is to search out these more complicated possibilities.

Constructing a scheme to aid us is our first problem. It is instructive to begin by surveying the scope of the problem. In the study just completed, we tested all possible pairs of elements to form compounds, including the possibility of elements combining with themselves. This turns out to be nearly 625 possible compounds -- not all distinct. For, if we take each element and test it with all twenty five others and repeat this twenty five times for all elements to insure that we have tested all possibilities, we would have 25 x 25 possibilities, some of which would be duplications. The number of test we have to perform is easily manageable. As we turn to more complicated compounds the number of possibilities increases rapidly. Consider, for example, a compound composed of two elements, but in a two-to-one ratio, for example two parts H and one part O to form H_2O.

Problem:

1.3.1. Estimate the number of possible compounds formed in a two-to-one ratio from among 25 different elements, by the method used above.

1.3.2. Compare this estimate with that for compounds formed in a one-to-one ratio.

1.3.3. Improve your estimate in both cases by subtracting from your count the number of duplications and compare the resulting numbers of the two sets of distinct possibilities again.

[Note: The compounds HF and FH are the same where as HHO and HOO are not.]

The results of this comparison shows that there are precisely 625 distinct compounds that can be formed from elements in a two-to-one ratio if we include the 'compound' formed by an element combining with itself. While the number for the compounds formed from one-to-one ratio of elements is considerably less. Thus, as the complexity of the compound grows the number of possibilities grows.

Problem:

1.3.4. Ennumerate the other kinds of distinct compounds that may be formed using only two elements.

This problem discloses an innumerable number of possibilities. We may have two elements combine to form compounds in ratios of 3-to-1, 4-to-1, 5-to-1,...2-to-3, 2-to-4, 2-to-5,...3-to-4, 3-to-5, 3-to-6,...etc. Clearly even the ennumeration of the types of compounds is astronomically large, with each type of compound containing 625 possibilities. And our count of the possible compounds have only begun. As a final example, we consider compounds formed of three elements.

Problem:

1.3.5. Estimate the number of possible compounds formed from three elements in a 1-to-1-to-1 ratio.

The result of this problem shows that the number of non-distinct compounds of this type is 25 x 25 x 25 or 15,625. The number of necessary laboratory tests becomes unmanageable.

Problem:

1.3.6. For tri-elemental compounds ennumerate the kinds of ratios of elements that one may use to search for distinct compounds.

The results of this problem shows the types of ratios one may find in a compound are:

2-to-1-to-1 2-to-2-to-1 3-to-3-to-1

3-to-1-to-1
4-to-1-to-1
5-to-1-to-1
...etc.

3-to-2-to-1
4-to-2-to-1
5-to-2-to-1
...etc.

4-to-3-to-1
5-to-3-to-1
6-to-3-to-1
...etc.

Again the enumeration of the <u>classes</u> of the possible compounds alone is fantastically large, each class requiring 15,626 test! Of course we could continue, counting four elemental compounds each with 400,625 non-distinct possibilities. The numbers stagger the imagination.

But this is the scope of the job, or at least one way to view it. When we are searching for patterns in phenomena we must be prepared to review mountains of data and consider innumerable possibilities. However, we are always sustained by the hope that the job is not as tedious as the enumeration of all of these possibilities might lead us to believe. There is always the faith that long before we have needs to consider even a small fraction of these data, a pattern will begin to emerge to rescue us. That is the faith and hope that drives all scientists.

A review of all of the possibilities also makes clear the sublime advantage of a useful pattern should we find one. It enables us to <u>predict</u> the results of all of the untried tests. We are able to know the whole of an astronomical scheme of possibilities by scrutinizing only a fraction of the evidence. This is the nub of scientific enterprise.

It is also important to recognize that although chance plays a role in whether or not we succeed, a great deal depends on our choice of data we choose to look at it and on how we use hints of evidence of small patterns in our search for larger ones.

4. **The Experiment:** Part II

Given the vastness of possibilities, it would be most reasonable to begin with the simplest class of large compounds outlined above, namely, the 2-to-1 ratio, bi-elemental compounds.

Assign each study group elements to research in a fashion similar to the experiment in Part I. For example, the group assigned to study hydrogen searches for a single unit of another element to combine with two units of hydrogen.

The Result

Using the concept of chemical classes developed in Part I and the language generated to accommodate it, we have succinctly recorded a representation of the result of this study in figure 6 .

5. **Analysis:** Part II

Patterns

(a) The most obvious feature of this data is implicit in the language used to record it, namely, that the usefulness of the concept of chemical classes persist. Moreover, that elements behave in a similar fashion as the ones defined in the first set of experiments. Thus, we may view this data as giving us additional information about the combination patterns of the elements. We have no evidence of behavior contradictory to that observed earlier.

(b) Secondly, it is clear that a single chemical unit has

A REPRESENTATION OF THE EMPIRICAL COMBINATION PATTERN OF ELEMENTS FORMING COMPOUNDS IN A TWO-TO-ONE RATIO

$$\begin{bmatrix} \mathrm{HH} \\ \mathrm{NaNa} \\ \mathrm{LiLi} \end{bmatrix} \Longleftrightarrow \begin{bmatrix} \mathrm{O} \\ \mathrm{S} \\ \mathrm{Se} \end{bmatrix} \; ; \; \begin{bmatrix} \mathrm{FF} \\ \mathrm{ClCl} \\ \mathrm{BrBr} \end{bmatrix} \Longleftrightarrow \begin{bmatrix} \mathrm{Be} \\ \mathrm{Mg} \\ \mathrm{Ca} \end{bmatrix}$$

$$\begin{bmatrix} \mathrm{BeBe} \\ \mathrm{MgMg} \\ \mathrm{CaCa} \end{bmatrix} \Longleftrightarrow \begin{bmatrix} \mathrm{C} \\ \mathrm{Si} \\ \mathrm{Pb} \end{bmatrix} \; ; \; \begin{bmatrix} \mathrm{OO} \\ \mathrm{SS} \\ \mathrm{SeSe} \end{bmatrix} \Longleftrightarrow \begin{bmatrix} \mathrm{C} \\ \mathrm{Si} \\ \mathrm{Pb} \end{bmatrix}$$

$$\begin{bmatrix} \mathrm{BB} \\ \mathrm{AlAl} \\ \mathrm{GaGa} \end{bmatrix} \Longleftrightarrow \text{Nothing;} \quad \begin{bmatrix} \mathrm{PP} \\ \mathrm{NN} \\ \mathrm{AsAs} \end{bmatrix} \Longleftrightarrow \text{Nothing;} \quad \begin{bmatrix} \mathrm{HeHe} \\ \mathrm{NeNe} \\ \mathrm{ArAr} \end{bmatrix} \Longleftrightarrow \text{Nothing}$$

figure 6

different chemical properties than two chemical units of the same element. For example, H has different chemical properties than HH.

It allows us to maintain faith in the general concept of chemical classes since most of these results could be anticipated after finding a key compound. For example, if we interpret the statement "H, Na, and Li are in the same class and the O,S, and Se are in the same class but different from that of the first group" to mean that Na and Li always behave exactly like H, and S and Se always behave like O, then on "discovering" the key compound HHO, it would have been possible to predict the other 8 compounds formed from elements of these two classes. For example, if Na acts exactly as H, then NaNa acts as HH; then NaNa is the same class as HH. Consequently, if HHO forms a compound so does NaNaO.

Problem:

1.4.1 Using an analysis similar to that above, given the classification of elements obtained in part I and the fact that HHO is a compound, prove that HHS is a compound.

1.4.2 In a similar fashion, given that H, and Na are in the same chemical class and that HHO is a compound, predict that NaOh is a compound.

One way of viewing these data is that it enables us to relate elements in different chemical classes. For example, this second set of data represented in figure VI, may be interpreted as evidence that HH, NaNa and LiLi are in the same chemical class as Mg.

Problems:

Using the original listing of chemical classes, the extended definition of chemical classes (i.e. that two elements in the same class always act the same) and the fact that HHO is a compound, show that it follows that:

1.4.3. NaNa is in the same class as Mg.

1.4.4. NaNaS is a compound.

1.4.5. NaOH is a compound.

Relation Among Four Classes

So far, our use of these new experimental facts have enabled us to draw a number of useful conclusions about relationships among elements in two classes on the basis of experimental evidence of the existence of a single compound formed from one element from each of the two classes. But the concepts employed are even more general and far reaching than that. If we introduce as additional grist, the law of multiple proportions, we can relate the elements in four classes on the basis of the existence of a single compound. For example, the law of multiple proportions can be used to prove that if HCl is a compound, then HHClCl is a compound. Then if HHO is a compound it implies that ClCl is in the same class as O. Then using the experimental evidence of part I that CaO formed a compound, we may conclude that CaClCl form a compound. Hence, we have interelated the classes.

$$\begin{bmatrix}\mathrm{H}\\\mathrm{Na}\\\mathrm{Li}\end{bmatrix} \quad \begin{bmatrix}\mathrm{Cl}\\\mathrm{F}\\\mathrm{Br}\end{bmatrix}, \quad \begin{bmatrix}\mathrm{O}\\\mathrm{S}\\\mathrm{Se}\end{bmatrix}, \quad \begin{bmatrix}\mathrm{Be}\\\mathrm{Mg}\\\mathrm{Ca}\end{bmatrix}$$

[Note: *The implication that the formula HHClCl forms a "compound"* *does not have the traditional atomic interpretation that a molecule is formed by two atoms of hydrogen and two of chlorine. We have avoided an atomic interpretation of our results and maintained only that the formula HHClCl denotes the proportions in which these elements combine to form a substance with new chemical properties.*[1]

Problems:

1.5.6. By experimentally testing several cases, verify with the compound detector that if two elements combine to form a compound in a two-to-two ratio.

1.5.7. Prove that this is a logical consequence of the law of multiple proportions.

Prove that if HHFF is a compound and HHO is a compound, then:

1.5.8. FF is in the same class as O

1.5.9. HH is in the class as Ca

1.5.10. ClCl is in the same class a Be

1.5.11. LiHS can be predicted to be a valid compound.

The relationship among the four chemical classes developed above coupled with the law of multiple proportion extended a step further is profoundly powerful, for it contains information about a sub set of the innumerable classes of compounds we have outlined above, namely, that all those involve only elements from those four classes. Just as we were able to predict the existence of the compound NaOA from the compound HHClCl, so we are able to predict the existence of any number of larger compounds the same way. For example:

Problem:

Experimentally verify that HHHFFF is a compound.

Show that this follows from the law of multiple proportions.

Show that since, HH is in the same class as Be and FF in the same class with O, the following compounds are possible:

1.5.12 HHCaFFF
1.5.13 CaCaFFF
1.5.14 CaCaOFF
1.5.15 HHCaOO
1.5.16 NaNaBeSS
1.5.17 LiLiMgSeO

A similar analysis can be used in reverse to test whether theoretically any compound composed solely of these four elements is possible. For example, if we would like to know whether the combination HClFOO forms a compound or not, we need only replace all elements by their F or H equivalents and see if the result contains these two elements in a one-to-one ratio.

Problem:

1.5.18 Use the scheme suggested above to test whether HClFOO should theoretically be a compound.

1.5.19 Verify your results experimentally with the compound detector.

In this fashion we can correctly predict the existence of all possible compounds that contain only elements from these four classes. We have arrived at our universal law, at lead for four classes of elements.

6. Review

At the conclusion of this section, the advantage of the concept of chemical classes is firmly established and we have developed a scheme to expedite our search for more complicated compounds. We have discovered a universal law, relating four out of the eight of the chemical classes. It is a natural extension to search for larger compounds in the same fashion.

7. The Experiment: Part III

This part of the experiment is necessarily different from the first two because we now have an efficient method of researching new compounds. We need only establish a connection between H and one element in the P , N, and As class and finally a connection between H and one element in the C, Si, and Pb class. From this, we may predict how H combines with all the rest. Using the law of multiple proportions, we can then establish connections between the elements in all 8 classes. Assign to all groups, the project of researching separately the combination patterns of HHH and HHHH as these groups combine with one other element.

Problem

1.7.1. Using the results of the previous study, show that HHH or HHHH will not combine with a single unit of any of the other elements considered so far.

8. Analysis

The Results

The results of this study show that:

(a) HHH combines with a single unit of each of the elements: P, N, and As.

(b) HHHH combines with a single unit each of the elements: C, Si, and Pb.

With these results our study is complete. We are now in a position to correctly predict all possible compounds that may be formed using the twenty five elements we have studied. Or conversely, we may assess the ability of any combination - no matter how complicated - of elements offered us to form a compound.

A Statment of the Law of Chemical Combinations

In section 4 we developed a scheme for predicting whether any given combination of elements formed a compound, so long as the classes from which the elements were taken were 'related'. By a careful analysis of the steps of this scheme we may extract a statement of a law of chemical combination.

Problem:

1.7.2. Develop a fool proof set of instructions for the following the scheme given in section 4 under "Relations Among Four Classes" to predict whether or not a given combination of elements will form a compound. The statement must be sufficiently clear that a person who knows no chemistry may follow your directions and theoretically predict which combinations of elements form compounds no matter how many elements are involved or in what ratio.

We may arrive at a statement of this law as follows, beginning with a review of the main features of our data so far:

(a) All elements may be divided into one of two classes, either a H (hydrogen) 'like' class or F (florine) 'like' class.

(b) We may associate an 'equivalency' number with each chemical class that is equal to the number of units of hydrogen equivalent to one unit of an element of that class.

For example, all single units of the elements in the Be (Berilium) class are equivalent to HH (two units of hydrogen) We may state these results briefly in the schematic form:

$(Be)_{class} = 2(H)_{class}$; $(O)_{class} = 2(F)_{class}$

$(B)_{class} = 3(H)_{class}$; $(N)_{class} = 3(F)_{class}$

$(C)_{class} = 4(H)_{class}$; $(C)_{class} = 4(F)_{class}$

The method for testing the validity of a compound, requires that we replace each of the hydrogen 'like' or florine 'like' elements in the compound by its equivalent number of hydrogen or florine units. Once the conversion is completed and the'prospective' compound is given in terms of units of only hydrogen and florine, we need only count the numbers of units of each. If the number of hydrogen units equal the number of florine units, the hydrogen-florine collection, as well as the original collection of elements, is a compound. A concise statement of the rule is given as: "If the sum of equivalency numbers of the hydrogen like elements in a prospective compound is equal to the sum of the equivalency numbers of its florine like elements, the compound is a valid one."

This law is equivalent to the well known law of chemistry which uses the notion of valence. It states that "Any combination of units of elements form a compound if the algebraic sum of the valences associated with each of the units of the constituent elements totals zero." Valence is a numerical quantity assigned to represent the combining tendency of the elements. In addition to a magnitude it is also given a sign of plus or minus.

TABLE I . EQUIVALENCY NUMBERS OF CHEMICAL ELEMENTS

	Hydrogen 'Like" Elements				Florine 'Like' Elements			
Equivalency Number	1	2	3	4	1	2	3	4
Element	H	Be	B	C	F	O	N	C
	Li	Mg	Al	Si	Cl	S	P	Si
	Na	Ca	Ga	Pb	Br	Se	As	Pb

figure 7

TABLE II. VALENCES OF THE CHEMICAL ELEMENTS

Valence	+1	+2	+3	+4/or-4	-3	-2	-1	Inert
Element	H	Be	B	C	N	O	F	He
	Li	Mg	Al	Si	P	S	Cl	Ne
	Na	Ca	Ga	Pb	As	Se	Br	Ar

figure 8

PROBLEM SET III: CHEMICAL REACTIONS

** 1. A ton of water contains 1776 lbs. of oxygen. Oxygen helps fire to burn. Yet water is used to extinguish fires. Explain why this is so.

* 2. What is the difference between a physical change and a chemical change? Give one example of each.

* 3. After a stick of wood has been burned, the ashes weigh much less than the original wood. Discuss whether this experiment gives evidence to contradict to the law of conservation of matter.

** 4. From experimental analysis, a research chemist found the following reactions to occur when $AgNO_3$ is added to NaCl solution, H_2SO_4 is added to a $CaCl_2$ solution, and Na is added to H_2O:

$$AgNO_3 + NaCl \longrightarrow \underset{\text{white solid}}{AgCl\downarrow} + HNO_3$$

$$Ca(NO_3)_2 + H_2SO_4 \longrightarrow \underset{\text{white solid}}{CaSO_4\downarrow} + 2HNO_3$$

$$Na + H_2O \longrightarrow NaOH + H_2\nearrow$$

Based upon the classifications you obtained using the data from your chemical slide rule, what other substances would you predict to behave as NaCl, Na and $Ca(NO_3)_2$?

** 5. In one of your reference books, Isaac Asimov's <u>A Short History of Chemistry</u>, there is an excellent description of how scientists classified all the elements according to chemical families. Please read pp. 125-145 and answer the following questions:

   a. Describe the basis upon which Lothar Meyer developed his periodic table.

   b. Describe the basis upon which Dmitri Ivanovich Mendeléev developed his periodic table.

c. Would Mendeléev and Meyer's table correspond to the same classification of elements into the same groups? Explain your answer.

d. Explain how Mendeléev used his periodic table of elements to make predictions about the properties of elements which had not been discovered in 1869. When these elements were discovered, did their properties agree with Mendeléev's predictions?

* 6. Explain how chemists use the periodic table of elements to make predictions about the probability of chemical reactions of unknown chemicals.

E. CHEMICAL ACTIVITY

In this section we study the patterns that govern chemical changes. This is the basis underlying the nature of chemical reactions and the working end of chemistry, the part on which technology is based. With a knowledge of the chemical change occurring, we are able to control the process and subsequently our environment. Chemical change is a fundamental and continuous process of this planet. Although elements are usually found in nature in combination with each other in compounds, they do not remain in that state forever. Under proper conditions two compounds can be brought together and induced to undergo a spontaneous change whereby the elements of the compounds reorganize themselves into new groupings to found new compounds. This change is called a chemical reaction. Sodium hydroxide (NaOH) and hydrochloric acid (HCl), for example, when mixed, undergo a chemical reaction to produce a mixture of two new compounds, sodium chloride (NaCl) and water (H_2O). Similarly when ammonia (NH_3) gas is exposed to oxygen (O_2) at high temperatures, a reaction takes place. As a result, two new compounds are formed, nitrogen gas (N_2)* and water (H_2O). This is a chemical description of a familiar process, the burning of a gas.

These are natural chemical processes that occur unaided, reflecting some of the laws of chemistry. Precisely what the law is

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* Nitrogen gas (N_2) is considered a compound inasmuch as two nitrogen atoms are chemically bonded together.

at this point, we do not know. We do know, however, that there is a law which must exist (i.e. there is some pattern by which the elements recombine to form specific new compounds), because of the fact that the reactions are reproduceable and reliable. Whenever we combine NaOH with HCl or NH_3 with O_2 at high temperatures and pressures, the chemical products are always the same. We can also presume that the law must contain information about the properties of elements that our conceptual law does not give, since the first law is capable of predicting only which new compounds may legitimately be formed, but not which will indeed actually form. For example, In the reaction between NH_3 and O_2 at high temperature and pressure, can it be possible that nitrogen can combine with oxygen and liberate hydrogen? If we are to learn what this law is we must obtain additional information about the behavior of chemical elements and the compounds they form. As the law we seek pertains to the patterns of chemical change, it is reasonable that we begin our search by studying chemical reactions. To simplify our problem, we begin below by studying one of the cases of simple reactions, namely reactions between a compound composed of only two elements and pure elements. This simplifies the problem as we will have to look for patterns of recombination only among three elements.

EXPERIMENT II "REACTION BETWEEN HCl AND METALS"

Equipment: Three medium sized test tubes per two students

Chemicals: 3 M solution of HCl. Sample of approximately 6 metals - Zinc (Zn)strips,lead(Pb) strips, copper(Cu) wire, iron(Fe) nails, aluminum(Al) wire, lumps of magnesium(Mg). The sizes of the sample should be approximately 1 to 2 cc.

Procedure:

Place five ml. of 0.1 M HCl in each of three test tubes. Add a sample of metal to each of the test tubes so that there is only one metal in each tube containing the solution of HCl. The purpose of using three test tubes at one time is to decrease the time for the entire experiment.

Observe and record the results. Describe any action that takes place indicating that a chemical change may be taking place. Generally speaking, chemical changes are easiest to identify when there are changes in properties such as color, odor, or physical state accompanied by the formation of a new product (if two liquids are mixed and a solid appears in the solution or a gas appears this is a change in physical state. A liquid becomes a solid or a gas). Hence one may look for these property changes as a preliminary clue to chemical reactions.

Pour off the solution and empty the contents of the test tube. Wash the container and repeat the experiment until each of the metal samples have been placed in a tube containing a solution of HCl.

Suppose upon adding a metal that we will call "Z" to a solution of HCl, we observe the metal disappear in the liquid and at the same time bubbles are created around the dissovling metal. Let us further suppose that the metal "Z" is in the same chemical class as H*.

Identify the new compound formed and the new element that is freed. Write an equation to represent the reaction.**

Suppose that we have no idea of the chemical class in which the metal is found. Write an equation to represent each of the possible chemical reactions. Suppose that only one of the elements appearing in the set is a gas at room temperature, will this additional information help you to further identify the reaction products? If so, how?

PROBLEMS:

1. On the basis of your observations, identify the metals that react with a solution of HCl.

---

* Although hydrogen exist in the free state as a diatomic molecule, H_2, the notation H will be used in this discussion to keep the concept of hydrogen as an element on the simplest level.

** Some students may tend to identify chlorine as the new element (gas) being formed while others may choose hydrogen or even oxygen from the water which merely serves as a medium in which the reaction occurs. The instructor may resolve these ambiguities by having his student insert a glowing splint momentarily over the evolved gas and noting that it is extinguished. This elminates oxygen as the metal being evolved. Student should then be directed to look up the properties of chlorine and hydrogen in any standard general chemistry text to make the final decision that hydrogen is the element formed. Three typical references are Keller, E. "Hydrogen the Simplest" Chemistry, 42(10), 1969; Johnson, R. C., Introductory Descriptive Chemistry, W. A. Benjamin, Inc., N. Y. 1966 (paperback) and King and Caldwell, "College Chemistry", American Book Company, Fifth Edition, 1967.

This information is rather meager and may appear to be not of much value. A model may help us to order this information and make use of it.

Suppose we interpret the results of the reaction:

$$Z + HCl \longrightarrow ZCl + H$$

as inferring that since the metal "Z: reacts with HCl to form the new compound ZCl, it is because "Z" has a stronger preference for Cl than H has. Notice this is only a descriptive interpretation of the reaction. It does not add any new information. It has only stated that there is a preference, without stating what the preference means or giving any details or criterion by which the selections are made. In short, this is in effect just a way of describing the results - a description that nonetheless has a value.

PROBLEMS:

Suppose we have information about another metal "X" which when added to a solution of HCl does not undergo a reaction. Using the model which attributes reactions to a strength of preference of one element for another, what conclusions may you reach regarding the relative preferences of element "X" and H for Cl?

Using the above information, list the three elements, "X","Z", and H in decreasing order of strength of preference for Cl.

On the basis of this list predict the results of the following reactions: [If there is no reaction indicate this fact].

$H + ZCl \longrightarrow$

$H + XCl \longrightarrow$

$X + HCl \longrightarrow$

$Z + XCl \longrightarrow$

$X + ZCl \longrightarrow$

Analysis:

The information we have given above is:

$Z + HCl \longrightarrow ZCl + H$ Thus, Z preference for Cl is greater than H preference for Cl.

$X + HCl \longrightarrow$ no reaction Thus, H preference for Cl is greater than X preference for Cl.

Thus, the elements in increasing order of preference for Cl are:

Z preference is greater than H which is greater than X.

Therefore, we may use this listing to make the following predictions about the reactions:

$H + ZCl \longrightarrow$ no reaction

$H + XCl \longrightarrow X + HCl$

$X + HCl \longrightarrow$ no reaction

$Z + XCl \longrightarrow ZCl + X$

$X + ZCl \longrightarrow$ no reaction

The above examples point up very clearly the value of classifying elements according to the "strength of preference" for another element in the formation of a compound. By use of this scheme we are able to make predictions about the outcome of untried reactions, which is the goal of our study. It turns out that as a rule of thumb, we need not restrict this study to elements in the same chemical class, i.e. if Fe has a stronger preference for Cl than H does, then on the basis of that information alone we predict that adding Fe to a solution of HCl will produce the products, H and $FeCl_2$.

It also turns out that it is a good rule of thumb that if an element has a stronger preference for a given element than another, it will have a stronger preference for all other elements with which the latter forms similar compounds.

PROBLEMS:

Given the reactions

$Y + HCl \rightarrow YCl + H$

$H + XCl \rightarrow HCl + X$

(a) predict which of the reactions will occur:

$Y + H_2S \rightarrow$

$Y + XBr \rightarrow$

$H + YCl \rightarrow$

PROBLEMS:

Given the following set of data regarding reaction patterns, construct a comparative list of the preference strength of the elements Cd, Pb, Ni, Sn, and Co.

$Co + CdSO_4 \rightarrow$ no reaction

$Co + NiSO_4 \rightarrow CoSO_4 + Ni$

$Co + SnCl_2 \rightarrow CoCl_2 + Sn$

$Co + Pb(NO_3)_2 \rightarrow Co(NO_3)_2 + Pb$

The information contained in these reactions is not sufficient for you to be able to identify uniquely the combining strengths of each element. There may still be pairs of elements whose relative strengths remain unknown. For example, if one particular element is found to have more combining strength than two others, it should be possible to find further reactions which can establish the comparative strengths of the three elements in question. Hence, with reference to the above equattions

(a) Make a list of the order of strengths of the elements involved.

(b) What is the smallest number of additional equations you would need in order to be able to construct a unique list of the elements in the order of increasing combining strength?

(c) Identify the pairs of elements the reactions between which you need in order to make your list complete.

(d) Recommend the reactions that would enable you to make the necessary distinction.

By carrying out experiments similar to the ones you have conducted to determine the relative chemical activities of a limited number of elements, chemists have deduced a comprehensive table of relative chemical activities or "preference" of elements for replacing hydrogen from a solution of HCl. The results of their work is summarized in table III.

Table III List of Elements in Their Decreasing Order of "Chemical Combination Strength" or Continued Chemical Activity

Name of Element	Symbol	Name of Element	Symbol
Cesium	Cs	Zinc	Zn
Lithium	Li	Chromium	Cr
Rubidium	Rb	Iron	Fe
potassium	K	Cadmium	Cd
Barium	Ba	Cobalt	Co
Strontium	Sr	Nickel	Ni
Calcium	Ca	lead	Pb
Sodium	Na	Hydrogen	H
Magnesium	Mg	Bismuth	Bi
Berylium	Be	Copper	Cu
Aluminum	Al	silver	Ag
Manganese	Mn	gold	Au

PROBLEM:

As an application of the concept of "chemical combination strength" the following activity is suggested.

I. Using the listing a chemical activities given in table I., predict the outcome of the following chemical reactions:

$Zn + Cu(NO_3)_2 \longrightarrow$

$Zn + Mg(NO_3)_2 \longrightarrow$

$Mg + Zn(NO_3)_2 \longrightarrow$

$Mg + Cu(NO_3)_2 \longrightarrow$

$Cu + Mg(NO_3)_2 \longrightarrow$

$Cu + Zn(NO_3)_2 \longrightarrow$

II. Experimentally verify your predictions by using 0.1 M solutions of $Cu(NO_3)_2$, $Mg(NO_3)_2$, and $Zn(NO_3)_2$, a copper penny, a strip of magnesium, and a strip of zinc,

PROBLEMS:

* 1. Using the activity table of the elements, explain why iron deteriorates in water while copper does not.

** 2. Using the activity series for the elements suggest a chemical process for removing the gold from gold oxide (AuO).

* 3. Using the information contained in the activity series, contruct an argument explaining why gold is a better metal for tooth fillings than sodium.

* 4. Using the activity table of the elements, explain why gold and silver are called "noble" metals while sodium and zinc are characterized as active metals.

APPENDIX I

CHEMICAL COMPOUND DETECTOR

In order to introduce students to the principles of chemistry within the context of their own immediate experience, we have developed a set of devices that imitate the patterns of combination of the chemical elements as they form new compounds. During the initial stages of his introduction to chemistry he is encouraged without the technical complexities or dangers of a real chemistry laboratory. Studies made with these devices maintain the essential elements of investigations of real physical phenomena, measurement, recording observation, searching for patterns, and the thrill of discovery.

Below we describe the operation and theory of two devices of that operation as 'chemical compound formula detectors'.

The Mechanical Balance

Operation of the Balance

This version of the analogue chemical compound detector system is composed of an inexpensive two pan laboratory balance and two sets of systematically weighted packets. One set is constructed so that each packet represents (an atom of) a chemical element and is accordingly marked with the appropriate name or chemical symbol,while the other set is used as standards. In order to test whether two "elements" will combine we chose a combination of packets representing a possible compound, e.g., the combination "X and Y." The packet that represents element X and the packet that represents element Y are placed on the same side of the empty equilized balance. The balance will then, of course, shift to a position favoring the side with the X and Y packets on it. The standard weights, S, are then added one by one to the other side of the balance until: (a) the balance reverses its position and is then unbalanced in the opposite direction which indicates that they do not combine (in the fashion); or (b) the balance returns to the equilibrium position which means that, according to the balance scheme used, the elements may combine. See figures 9 and 10.

Theory of Balance

The principle on which the operation of the "compound detector" is based is equivalent to that on which the periodic table is based. A set of weighted packets which represent atoms of elements is constructed to be multiples of a basic (arbitrary) weight. The lightest packet, which is chosen to represent hydrogen, has a unit weight 1. The packets are arranged in order of increasing weight and a given packet weight is related to each element. A scheme is represented in the Table IV. Thus all elements whose valence is +2 will have a weight of 2 + a multiple of 8; etc. All elements with a valence of +4 or -4 will have a weight of 4 + a multiple of 8; all elements with a valence of -3 will have a weight of a multiple of 8 -3; all elements whose valence is -2 will have a value of a multiple of 8 - 2; etc. Thus any combination of elements which may combine to form an ionic compound must have a net zero valence and thus a total weight that is a multiple of 8. The standard packets which are used to balance the element packets are constructed so that each has a weight of exactly 8 times the weight of the unit packet representing hydrogen.

This system of assigning weights was used for all packets except those representing the inert gas element. The packets representing the inert gases are constructed so that they weigh a multiple of 8 plus a half unit. In this way, using relatively small numbers in packets for inert gases (i.e.) less than approx. 8), the inert gases will not be found to balance with any of the other elements, thus illustrating the inert chemical character of these elements.

The Slide Rule

Operation:

The slide rule version of the compound detector operates on the same principle as the mechanical balance version. But, it associates characteristic lengths on a rule with units of chemical elements. A working rule set is composed of two or more separate rules, one major rule and one or more minor rules, each marked with regular divisions, each of which represents a chemical element.

In order to test whether two elements, for example, X and Y, combine to form a compound in a one-to-one ratio of units of volume - or equivalently, if ten atoms of X combine with an atom of Y to form a diatomic molecule - one adds the lengths associated with each element by placing the left index of one rule over the division representing one element on the major rule, as shown in figure 11. If the division representing the other elements on the minor rule lies adjacent to a red marker on the major rule, as shown in figure 11(a) the two elements form a possible compound. If the division representing the second element on the minor rule does not fall on a red marker on the major rule, as shown in figure 11(b), the two elements do not combine in a one-to-one ratio to form a compound. In order to test whether the atoms of two or more elements combine to form molecules with more than two atoms, the process of adding the lengths associated with each atom of the prospective molecule is continued until the length associated with the final atom is added. If it is adjacent to a red marker on the major rule, as in figure 12, the test fails and the elements do not form a compound in that fashion.

The only limits to the size of the potential molecule being tested is the length of the major rule. If larger molecules are desired than there is room for on the major rule, construct an extension of the rule by adding equally spaced "red marked" divisions consistent with the division on the major rule.

Limitations

Because of the simplicity of its design, the compound has several limitations.

Single Valence

First and most obviously, the instrument is constructed to reflect a fixed, single valence for each element. It cannot, for example, admit both CO (carbon monoxide) and CO_2 (carbon dioxide) as valid compounds at the same time. The valence scheme used to construct the detector is given in table IV.

False Compounds

The more subtle limitation inherent in the design of the device is that it recognizes as correct compounds those with a net valence of multiples of +8 or -8 as well as zero. For example, HCl is correctly recognized as a valid compound by the detector, as it has a net valence of zero. But it will also admit, though incorrectly, H_8, H_{16}, Cl_8, or Cl_{16} as valid compounds. Similarly, it judges incorrectly more complicated collectons of elements such as Ca_3Mg (net valence of +8) or P_3H (net valence of -8). These errors should not, however, greatly inhibit the use of the detector as a valuable learning aid. It is most useful in the early stages of a chemistry course when one is not concerned with complicated compounds and there is little chance of encountering the false compounds. If it is used later in a course, for demonstrating the advantages of the periodic properties of the elements, for example, students are usually sufficiently advanced to be made aware of the limitations of the instrument and able to take the necessary precautions.

Table IV . WEIGHTING SCHEME FOR PACKETS REPRESENTING CHEMICAL ELEMENTS

+1 H 1	+2 Be 2	+3 B 3	+4,-4 C 4	-3 N 5	-2 O 6	-1 Fl 7	He 8
+1 Li 9	+2 Mg 10	+3 Al 11	+4,-4 Si 12	-3 P 13	-2 S 14	-1 Cl 15	Ne 16
+1 Na 17	+2 Ca 18	+3 Ga 19	+4,-4 Pb 20	-3 As 21	-2 Se 22	-1 Br 23	Ar 24.5

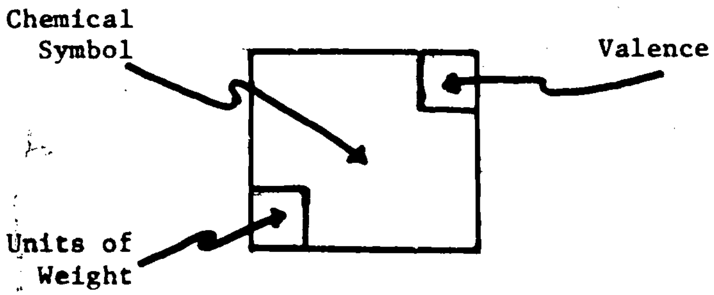
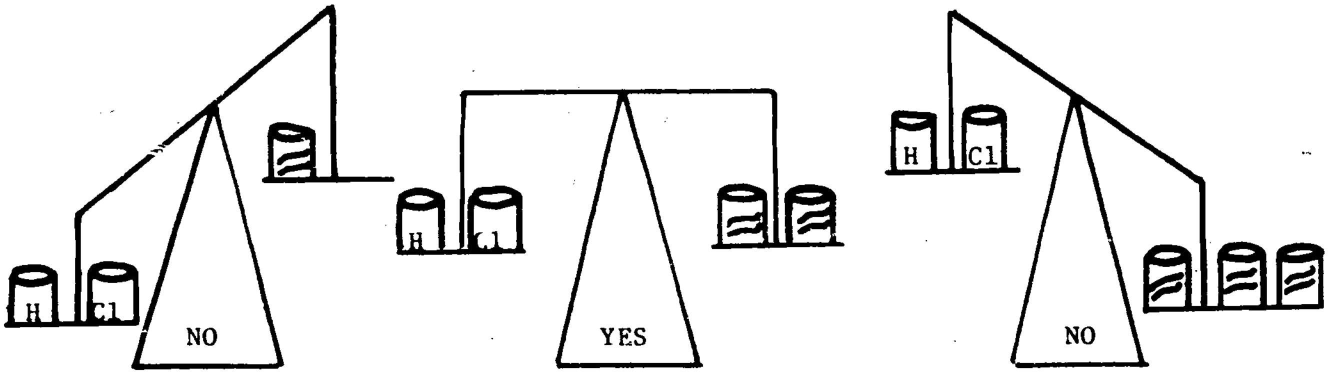


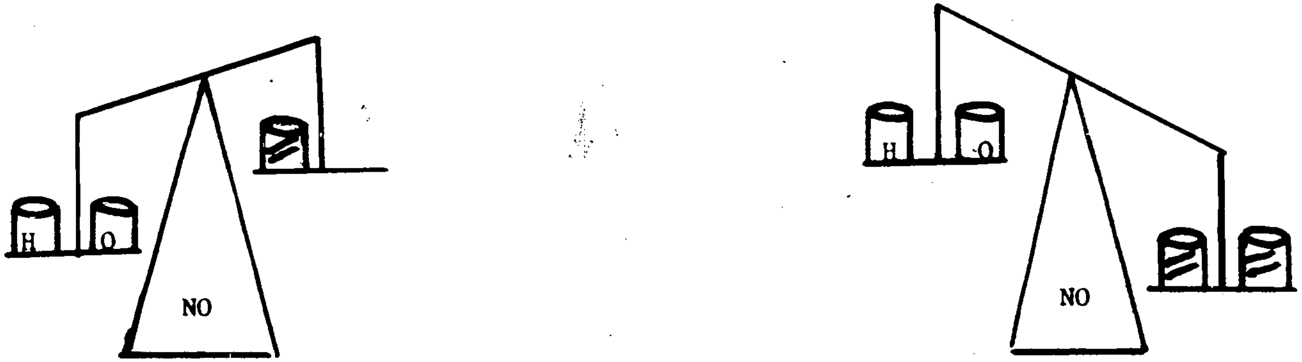
figure 9

OPERATION OF THE BALANCE VERSION OF THE COMPOUND DETECTOR



H (hydrogen)
and Cl (chlorine)
combine in a
one-to-one ratio
to form a
compound

(a)

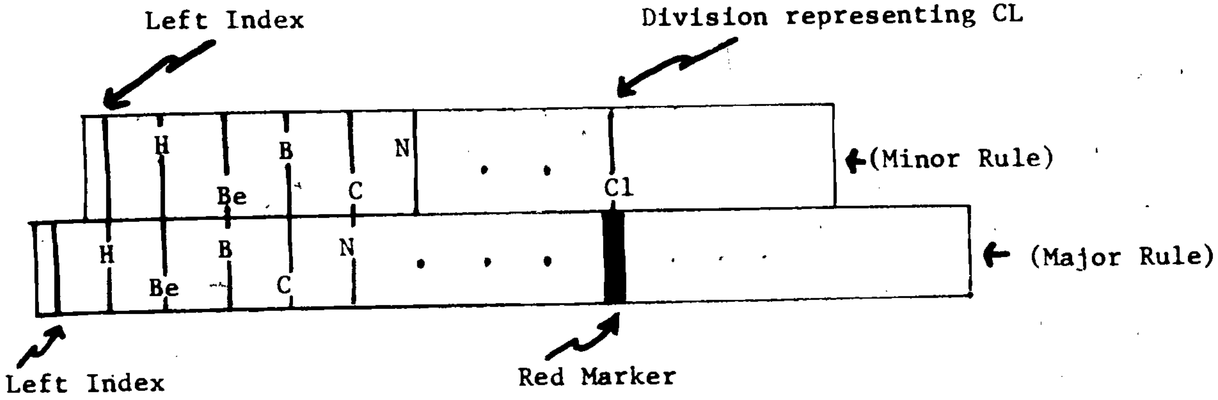


H (hydrogen)
and O (oxygen)
do not combine
in a one-to-one
ratio to form
a compound

(b)

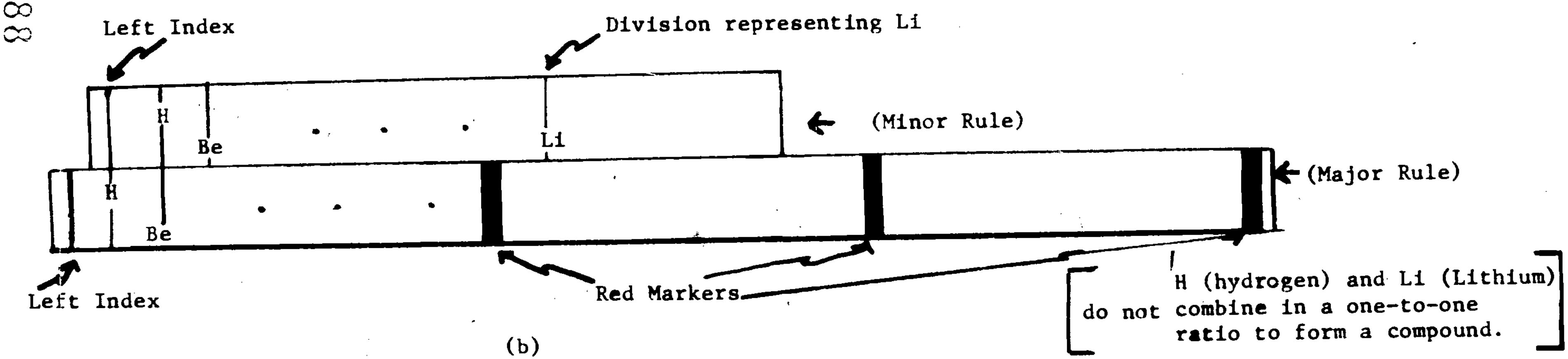
figure 10

USE OF THE CHEMICAL SLIDE-RULE



H(hydrogen and Cl (Chlorine)
combine in a one-to-one
ratio to form a compound

(a)

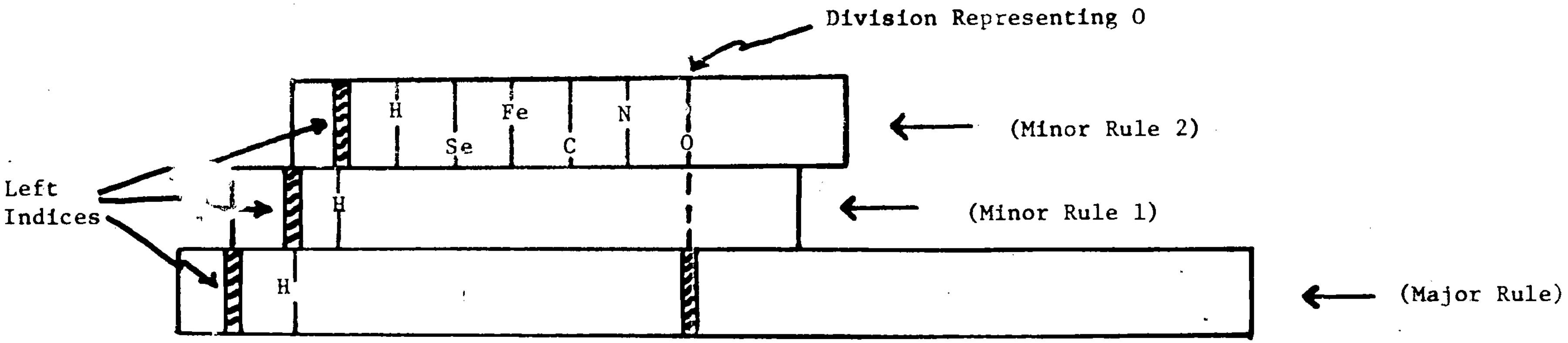


H (hydrogen) and Li (Lithium)
do not combine in a one-to-one
ratio to form a compound.

(b)

figure 11

USE OF THE CHEMICAL SLIDE-RULE



One unit of O (oxygen) and two units of H (hydrogen combine to form the compound H_2O

figure 12