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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. In this unit, the scientific method is discussed and illustrated with simple experiments that show how scientists acquire knowledge. Examples and experiments are provided to show how scientists use mathematics in discovering relationships in the physical world. Patterns in physical problems are demonstrated in a discussion of the simple pendulum and the simple lever. (MLH)

NATURE OF PHYSICAL SCIENCE

TEACHER'S CURRICULUM GUIDE

for the

Thirteen-College Curriculum Program

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ABOUT THE INSTITUTE FOR SERVICES TO EDUCATION

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.

ISE is headed by Dr. Elias Blake, Jr., a former teacher and is staffed by college teachers with experience in working with disadvantaged youth and Black youth in educational settings both in predominantly Black and predominantly white colleges and schools.

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From 1967 to the present, ISE has been working cooperatively with the Thirteen-College Consortium in developing the Thirteen-College Curriculum Program. The Thirteen-College Curriculum Program is an educational experiment that includes developing new curricular materials for the entire freshman year of college in the areas of English, mathematics, social science, physical science, and biology and two sophomore year courses, humanities and philosophy. The program is designed to reduce the attrition rate of entering freshmen through well thought-out, new curricular materials, new teaching styles, and new faculty arrangements for instruction. In addition, the program seeks to alter the educational pattern of the institutions involved by changing blocks of courses rather than by developing single courses. In this sense, the Thirteen-College Curriculum Program is viewed not only as a curriculum program with a consistent set of academic goals for the separate courses, but also as a vehicle to produce new and pertinent educational changes within the consortium institutions. At ISE, the program is directed by Dr. Frederick S. Humphries, Vice-President. The curricular developments for the specific courses and evaluation of the program are provided by the following persons:

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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, 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

The Thirteen-College Curriculum Program has been supported by grants from:

The Office of Education, Title III, Division of College Support
The Office of Education, Bureau of Research
The National Science Foundation, Division of the Undergraduate Education
The Ford Foundation
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
Florida A & M:	Ralph Turner	Lewis Allen	Robert Flakes	Melvin Gadson
Jackson State:	Dennis Holloway	Dennis Holloway	Dennis Holloway	Dennis Holloway
Lincoln:	Sabinus Christensen	Sabinus Christensen	Julian McCreary	Julian McCreary
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

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I. INTRODUCTION

What is the nature of science? This question is very important and in the past many attempts have been made to answer it in a short period of time and space. We deny the possibility of such a condensation. On the other hand, we believe that by practicing science the student will acquire a "feeling for the nature of science". Thus, our goal in writing this unit is to permit the student to engage in scientific investigation at different levels which will enable him to develop this feeling. Each section of the unit is self contained and may be used independently of the others depending on the needs and development of the students. It is hoped that the material will give the student a wealth of experience upon which his later work in science can be based. The discussion of science from a historical or philosophical standpoint is viewed as an extension to the primary material of this unit.

In keeping with the philosophy of using the inductive or "self discovery" method the experiments are designed to get the student involved in scientific investigation by using a scientific method. The student begins by using his everyday experiences to make his own observations, gather his own data and develop his own scientific method. The experiments move from familiar intuitive type problems requiring little or no use of measuring devices to the more abstract typically "scientific" problem where measurement and analysis of numerical data is a crucial part of the experiment.

Science should not be merely talked about. It involves a type of thought which must be experienced to be understood. Richard P. Feynman, one of the most prominent 20th Century physicists, has emphasized the emotional side of science.

> The same thrill, the same awe and mystery, come again and again when we look at any problem deeply enough. With more knowledge comes deeper, more wonderful mystery, luring one on to penetrate deeper still. Never concerned that the answer may prove disappointing, but with pleasure and confidence we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries - certainly a grand adventure.

To a scientist, then, science is both a "dreaming" and a "doing", it is creative endeavor, whose successful pursual cannot be assured by methodically following a fixed sequence of steps like baking a cake according to a faithful recipe. Contrary to popular notion, there is no single "method" that leads scientists unerringly to their discoveries. Although there are similar features that characterize what scientists do, scientific methods, as such, are as numerous as there are scientists. This notion is admirably expressed by Percy W. Bridgeman. He states:

> It seems to me that there is a good deal of ballyhoo about scientific method. I venture to think that the people who talk most about it are the people who do least about it. Scientific method is what working scientists <u>do</u>, not what other people or even themselves may say about it. No working scientist, when he plans an experiment in the laboratory, asks himself whether he is being properly scientific, nor is he interested in whatever method he may use <u>as method</u>...

In order to put across this notion of science we feel that the student must actually experience science. Consequently, all laboratory and classroom work in this unit has been designed to reflect a complete scientific process. Every attempt has been made to avoid materials which involve only one part of the process at a time (e.g., observation, classification, etc.). An exercise stressing merely observation alone is not "doing" science, but is merely talking about it.

The titles of the remaining sections of this unit are listed in the flow chart on page 4. As the titles imply, there is a natural hierarchal development as we go from the non-abstract to the abstract. But order is not immutable; nor is it necessary that each section of this unit be covered if the unit is to be used successfully. Each section is designed to be reasonably self contained so the end of that section may be used as an exiting point from this study of the Nature of Science. Moreover, to facilitate flexible use, each section has been written to conform as closely as possible to a single format given below.

SECTION STRUCTURE (NON-ABSTRACT LAB. ETC.)

A. Summary of the essential ideas contained in the sub-unit.

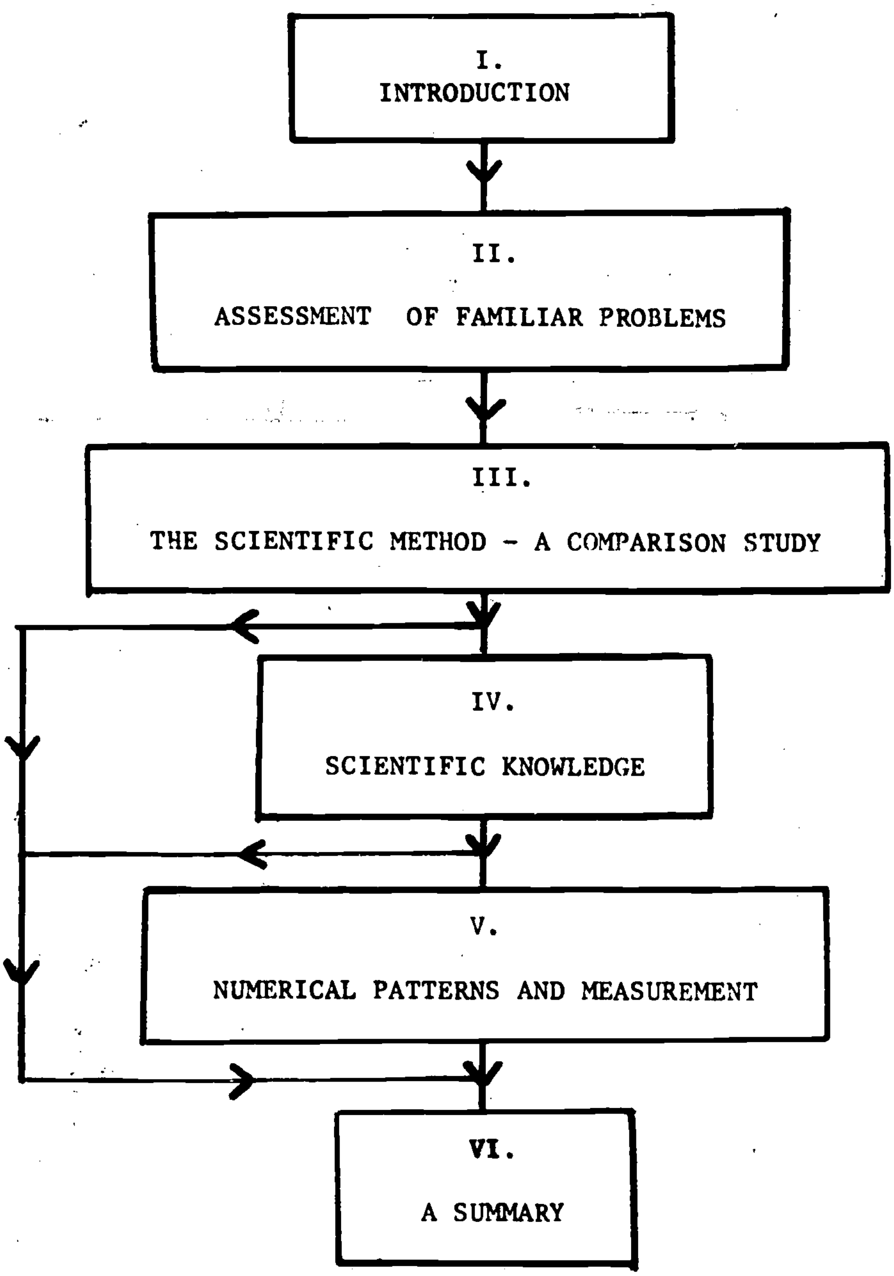
B. Examples of an Approach. This section describes a typical classroom experience which has had some success in the past.

C. Alternative Activities. A list of alternative laboratory work, discussion questions, or homework questions.

D. Suggested readings and other teaching aids where applicable.

The unit on the Nature of Science has been designed primarily to be used as an introductory part of the course; however, it does not have to be used for this purpose. It would be equally appropriate to end the course with some of the more sophisticated sections contained in this unit. The students would then get a chance to think about just what they have really learned during the semester.

UNIT FLOW CHART



Flow Chart for Alternate Usages of Unit

Fig. 1

II. ASSESSMENT OF FAMILIAR PROBLEMS

A. SYNOPSIS

We begin our study of the nature of science at the simplest level, namely, by analyzing some of the popular scientific notions of phenomena that are familiar to everyone. There are many scientific notions in our culture today which are so widely believed that they are accepted as being intuitively obvious. All of you have a considerable exposure to these notions. In effect, you will be thinking in a "scientific fashion" about ideas already very familiar to you.

The study is limited to a discussion format, the business of gathering data will be deferred until later since we are limiting ourselves to dealing with those things "commonly known" and analyzing what we know and how we know it. This gives us an opportunity to study the process of going from "observing" to "knowing" in a familiar context.

B. EXAMPLE APPROACH

The following gives a possible teacher-student dialogue concerning a very familiar experience.

T: There have been two conflicting ideas about what causes day and night:

i) The earth revolves on its axis.

ii) The sun revolves about the stationary earth.

Which is correct?

S: The first theory is obviously correct!

T: Have you ever seen the earth revolving?

S: No! I guess not.

T: But you have seen the sun going from one side of the sky to the other. So isn't it obvious that the second theory is correct?

S: Yes! That seems correct, but I know that it isn't correct.

T: How do you know then! Prove to me that the earth revolves in space.

S: I've thought of a lot of things and I can't seem to do it.

T: Well, is it possible that the first theory could be correct?

S: Yes! I can see that the sun would look like it traveled from east to west if the earth does revolve (like I know it does). I can picture in my mind sunlight falling on the earth, the earth rotating, and so on.

T: But you can also see how the second theory is correct. How, now can you decide which one is correct. Fortunately, in this class, you won't be burned at the stake for choosing to argue for the first theory.

S: Well, lets see! I could go into outer space and see. Today, in our modern age. I could actually see if the earth is rotating.

T: True! But in order to decide this question you must make sure your spaceship is stationary in space. For example, if your spaceship is in orbit about the earth, the earth would look like it was rotating even if it wasn't.

This particular question is a difficult one to resolve, mainly because we do not have direct and easy access to measurements of the system under discussion. There is no simple experiment one can perform to settle the issue. Theoretically one could - as stated above - man a spaceship to take him sufficiently far from the earth that he could make a direct visual inspection. But that experiment alone would not be sufficient, for he would have to make assurances about his own motion before being able to draw a conclusion about the motion of the earth.

The problem is not insolvable, however, and man did come to a conclusion that the earth was moving long before he had such expensive and powerful tools as spaceships. As it is well known, observations of the relative motion of the heavenly bodies coupled with the laws of physics settled the problem. Accounts may be found in several sources (See references 2 and 3). However, at this point, we are less concerned about "the correct" solution to this problem than we are about the criterion by which we chose one theory over another. The accounts cited provide good examples of the analytical process for reaching a decision. Before you study one of these articles make a comparison of the two models on the basis of the facts you already know.

Questions

1. List all the evidence that you can think of that supports the idea that the earth is rotating. List all of the evidence that contradicts that notion.

2. Weigh the two sets of evidence and on their basis alone reach your own conclusion about the motion of the earth.

3. Discuss the validity (or reasonableness) of these statements:

   (a) If the earth were rotating everyone would fall off.

   (b) The fact that oceans have tides is evidence of the rotation of the earth. As the earth rotates, the water "sloshes" around causing tides.

(c) If the earth were rotating, we would feel the push of the atmospheric wind as a result. The wind would be strongest at the equator than at the poles because points on the equator would be moving faster. But as this does not happen we must conclude, the earth is at rest.

(d) If the earth were rotating it would be slowed down by the friction with the atmosphere and, hence, slow down eventually. Since the earth is several million years old it could not still be rotating and must have stopped by now even if it were rotating at first.

(e) The earth is rotating, but so slowly that no instrument made on earth can detect it.

(f) Some evidence is more conclusive than others.

(g) If the most emminent scientist in the would says that the earth is rotating, then it must be so.

(h) If the most emminent scientist in the world says the earth is rotating, it is still only hearsay.

(i) Every man must determine for himself what is true.

(j) Since the majority rules, we can all vote on the issue of whether the earth is moving to decide the truth of it.

4. Outline the steps you used in coming to a decision so that the next time you face such a question you will have a procedure to follow to resolve it.

5. Study one of the references cited that contains an account of the resolution of the question of whether the earth is at rest or not. Compare the steps in your decision-making process to theirs.

6. What is scientific evidence?

7. How is scientific evidence used proving facts?

C. SUGGESTIONS FOR OTHER PROBLEMS

Using the methods and criteria developed in the preceding section, analyze the validity of the following statement.

1. The earth is a sphere floating in space.
2. The earth is flat.
3. The moon produces light of its own like the sun.
4. Moonlight is sunlight reflected off the moon.
5. Blacks are genetically inferior to whites.
6. Frog urine causes warts.
7. Your personality is determined by the month in which you are born.
8. Cigarettes cause cancer.
9. There is life after death.
10. Man evolved from the ape.
11. There are people with extra-sensory perception.

D. REFERENCES

1. "Modern Science and Human Values" by Everett W. Hall. This presents a very clear discussion of early astronomical ideas.
2. "The Sleepwalkers" by Arthur Koestler. This book contains an exciting account of the discoveries on which classical physics is based, as well as a privileged view of Koestler's

reconstruction of the personalities of some of the great scientists and the process of creation.

3. "Astronomy" by E. G. Ebbighauser, second edition, chapters 1 and 2. Published by the C. E. Merrill Co., Columbus, Ohio.

III. THE SCIENTIFIC METHOD - A COMPARATIVE STUDY

A. SYNOPSIS

This section is designed to assist the teacher in involving students in a variety of several separate scientific activities and then making a comparative study of these experiences at their conclusion. Each experiment has a different theme and approach; yet, each contains the elements of the entire scientific process. A comparison of the structures of these varied investigations will emphasize the general factors common to all scientific studies.

B. EXAMPLE ACTIVITIES

A description of each of the experiments is listed below. In the main they are written as teacher guides, although some have large sections of instructions for the student bordered from the rest of the section. These instructions taken as a whole from each section can be reproduced as laboratory directions for the students.

Assign students to work in small groups on the experiments. Several groups may work on the same experiment simultaneously.

When each group has completed its individual experiments or gotten sufficiently near a completion point that they have drawn some conclusions, it is asked to make a report of their findings. The essential information of the reports are to be written on the board to be evaluated by the class. With the teacher acting as research co-ordinator the following kinds of questions should be posed:

(a) How are the studies alike? That is:

(i) What was the first thing done in each case?

(ii) What was done as the last step in each experiment?

(b) When predictions were made, how were you able to determine whether they were correct or incorrect?

(c) Did your imagination play any part in your predictions <u>or</u> your observations?

1. Rock Studies

Material: None required

Data Collection

Preparation for this investigation begins before the regular class meeting. The assignment is simple. Students are to choose convenient areas around the campus, from which to gather a collection of small rocks and pebbles. At least ten samples from each area should be considered a minimum sample grouping. Each study group should sample at least three different areas.

Data Analysis

In the laboratory, examine the rocks carefully, noting and recording as many distinct properties of each rock as you need to identify it. Create categories to assist you in classifying your collection. For example, you might consider: color, texture, shape, size, and hardness. Do not limit yourself to only these properties but use others as well. Once a property is chosen, you should also be sure that you have some way of measuring it objectively so that if someone else classified it according to the same property he would reach the same conclusion as you.

After a complete description of each rock has been recorded, search for patterns in your data.

(a) Invent a rock classification scheme using the properties listed above as well as others you may think of.

(b) Do rocks of a given type have a variety of sizes or do they seem to occur in one natural size?

(c) If there is a variety of sizes within a rock type, what are the size variations?

(d) How do size variations differ from one rock type to another type?

(e) Is there a pattern in the groupings in which different rock types are naturally found, i.e., do certain kinds of rocks seem to be found only near other kinds of rocks?

(f) Is there a relation between different properties, e.g., do larger rocks have a higher degree of hardness?

Questions similar to those ao

(d) How do size variations differ from one rock type to another type?

(e) Is there a pattern in the groupings in which different rock types are naturally found, i.e., do certain kinds of rocks seem to be found only near other kinds of rocks?

(f) Is there a relation between different properties, e.g., do larger rocks have a higher degree of hardness?

Questions similar to those above may also be posed for the other properties. Do not limit yourself to using these questions only; they are meant to serve as a guide.

Application of Analysis

Using the above pattern of analysis, try to use your observations as evidence of some larger class of phenomena. That is, try to use your data to learn if there are some fundamental things that a study as simple as rock collecting can disclose. For those who are faint hearted in this part of the study, imagine what fantastic conclusions someone like the fictional detective Sherlock Holmes or Charlie Chan could draw from the thinest shreds of evidence. Thus use your data and try to answer such questions as:

(a) How might you explain relations between properties? For example, assume that it is found that the harder the rock, the larger its size in natural form; how would you explain this feature? Or suppose some students at Clark College in Atlanta found that all rocks have a reddish cast, even after prolonged washing, what might this suggest about the formation of the rocks in this red clay area of Georgia?

(b) What do the patterns of textures of different hardness of rocks or the patterns of sizes of rocks tell you about the weather of the area in which the rocks are found?

(c) What do the patterns (or lack of patterns) in the grouping of types of rocks tell about the evolution of the area?

Again, these questions are only guides; create as many others as you can to make full use of your findings.

2. The Inaccessible Die

Materials: There are no measuring devices needed in this study. It is necessary only to supply each study group with an "Inaccessible Die" system which is described in detail in the figure 2 below.

Abstract

The inaccessible die study is representative of studies of a number of phenomena in nature where the object under investigation may be probed only indirectly. No one has ever visually observed an atom; yet we infer its properties by its response to our probes. This experiment is designed to have students study a system by deliberately restricted means. They will not be able to hold it in their hands for "direct observation". Yet, they will be able to construct a model of the object they are studying with probablistic assurance that the model is correct.

Procedure

Each study group will be given a die enclosed in a box to study. As is indicated in figure 2, one has only a partial view of two adjacent faces of the die at one time. The faces of the dies in the boxes will be marked so that they are either black or white with the number of sides marked black varying from group to group. It is the purpose of the study to construct a model of the die using sightings of the sides that show through the observation window. By shaking the die, a new face may be made to show.

a. Minimum Evidence for a Model:

The study of the die is begun by closing one viewing window of the die case so that only one side at a time may be seen. Have the students observe the die.

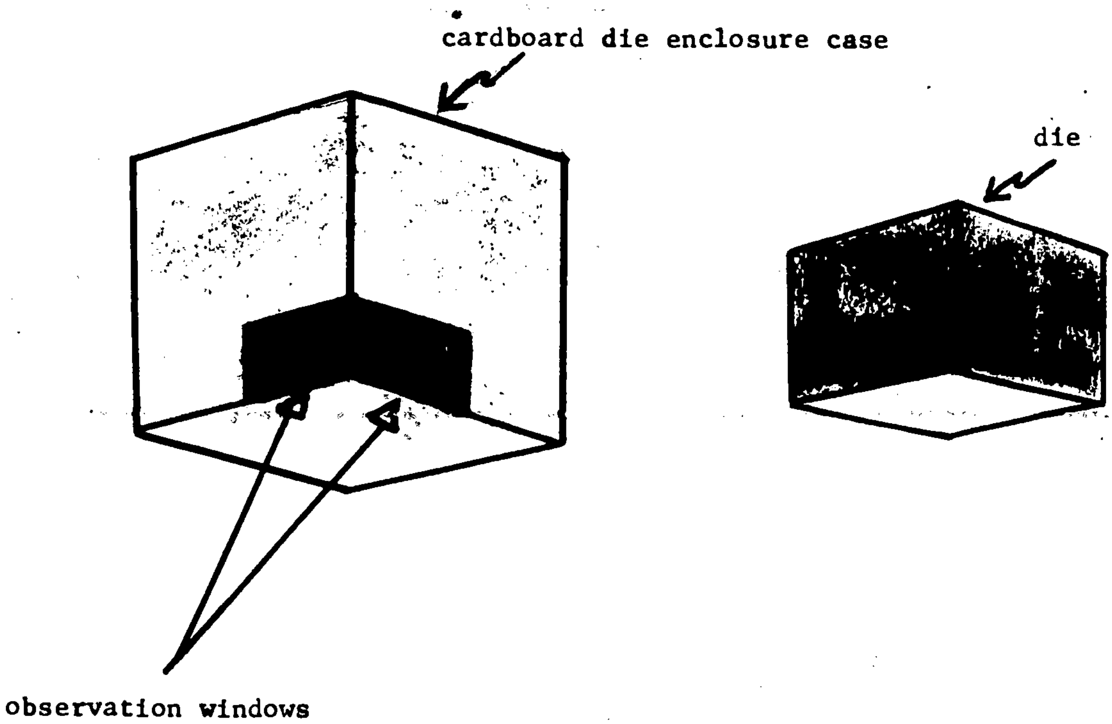


Fig. 2

INACCESSIBLE DIE SYSTEM

This system is composed of two elements, a die and simple cubic enclosure case as pictured above. The enclosure cube should have sides at least twice that of the die so that the die has room to rotate once placed in the case. The observation windows are squares with sides one-half that of one of the die faces. They may be as simple as holes covered by transparent sheets of plastic. A regular die may be used with each face covered with identical opague squares of cardboard marked to suit our purposes. Once the die is marked and placed in the case, the case should be sealed.

then follow the instructions below.

> Proceed to collect data constructing a model of what the die within the case looks like if all six sides could be seen simultaneously. Shake the case vigorously and record whether a black or white side is showing. Repeat procedure until there is data from three sightings then try to construct a model noting success or failure and reasons for either. If more data is required repeat procedure until enough data is taken and explain why the number of sightings chosen were necessary.

Asking the students to draw a model after only three sightings when he obviously does not have enough data, forces him to consider how many distinct faces he has seen. This is an appropriate point to interject the idea of the random arrangement of the dice as the case is shaken. He knows he has not seen every side after three sightings and maybe even then he has not seen three distinct sides. Even after twenty five throws he cannot be certain that there is a side that he has not seen. Every student has some intuitive feel for dealing with probability and knows about the long shot.

Students should be encouraged to discuss the probablistic application of their data within their research groups. Teacher guidance at this juncture will be important.

Each study group will generate a model of their die system at the conclusion of this phase of the study. Using the representation shown in figure 3, we have illustrated representative example of models that three different groups might construct along with the supportive data in figure 4.

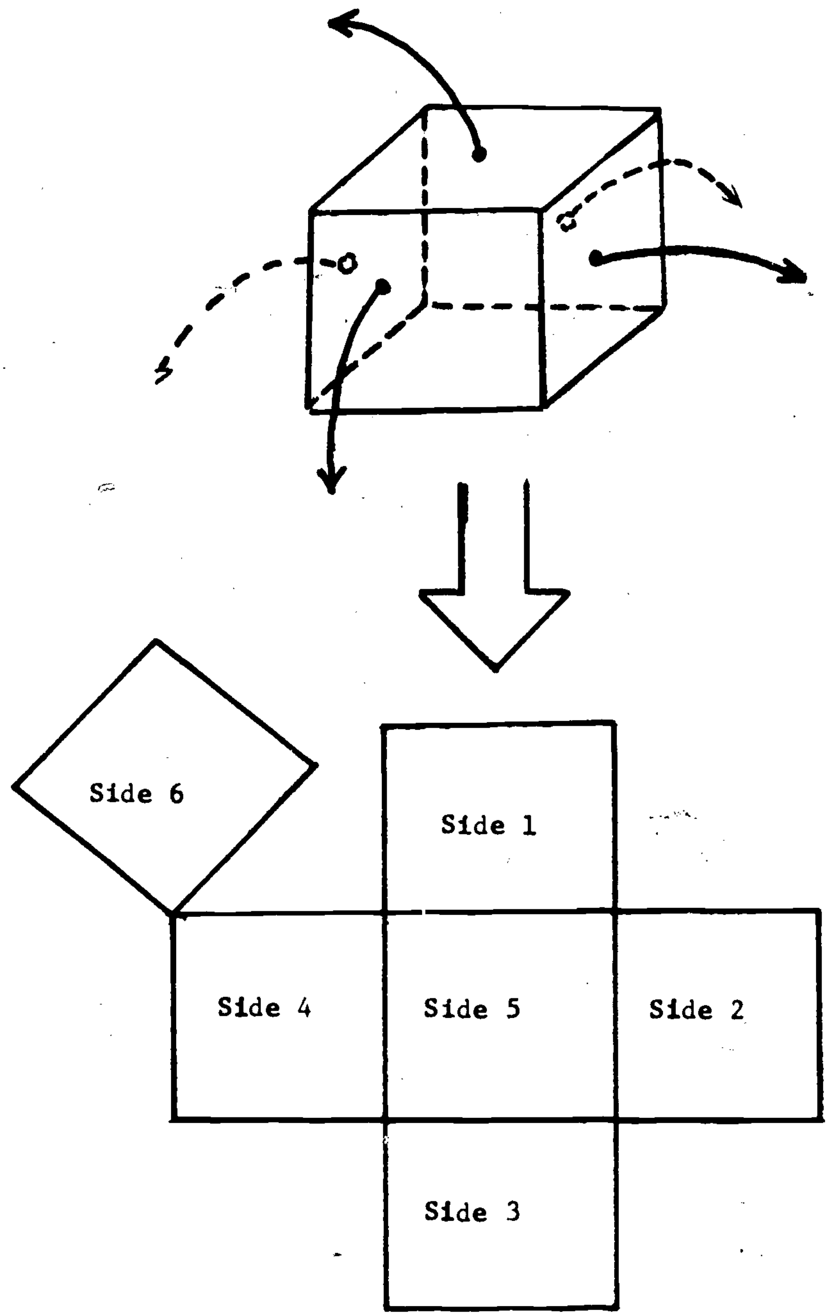
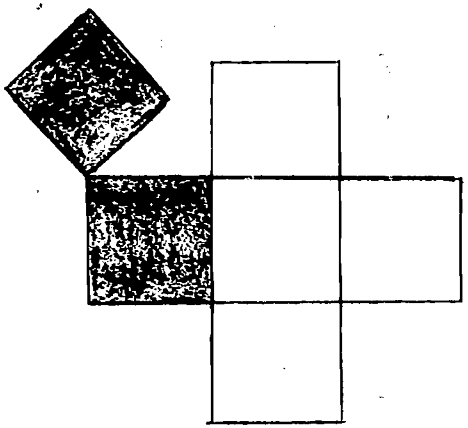


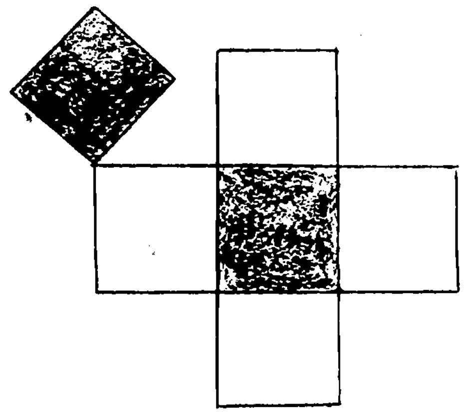
Fig. 3

To show a model of the three dimensional cube in two dimensions so that all six sides can be viewed at once, we use the representation shown above.

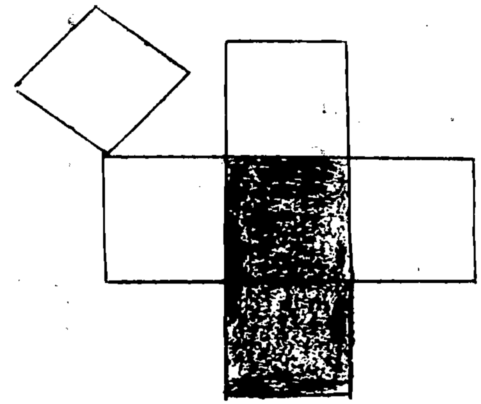
EXAMPLE DATA AND SUBSEQUENT
MODELS FOR ENCLOSED DIE



Group 1



Group 2



Group 3

Group 1

Trial	side	Trial	Side
1	B	9	W
2	W	10	W
3	W	11	B
4	W	12	B
5	W	13	W
6	B	14	W
7	W	15	B
8	W	16	W

Group 2

Trial	Side	Trial	Side
1	B	10	W
2	W	11	W
3	B	12	B
4	W	13	W
5	B	14	B
6	B	15	W
7	W	16	W
8	W	17	B
9	W	18	W
		19	W
		20	W
		21	W

Group 3

Trial	Side	Trial	Side
1	B	13	W
2	W	14	W
3	B	15	W
4	B	16	B
5	W	17	W
6	W	18	B
7	W	19	W
8	W	20	B
9	B	21	B
10	W	22	W
11	W	23	W
12	W	24	W
	W		

Figure 4

After a group has reached the stage of constructing a model similar to one of those shown in figure 4 from their data, the students should be asked to compare their model with other possible models generated by groups with similar statistical trends in their data.

Teachers Notes on the Structure of The Investigation

a. Collect the data - generate a model and scheme to describe the model. (How do you describe a 3 dimensional model on a 1 dimensional piece of paper?).

b. Raise question of equivalent models and how to distinguish between them. For example, below we show two equivalent models that could be generated using data obtained viewing one side at a time.

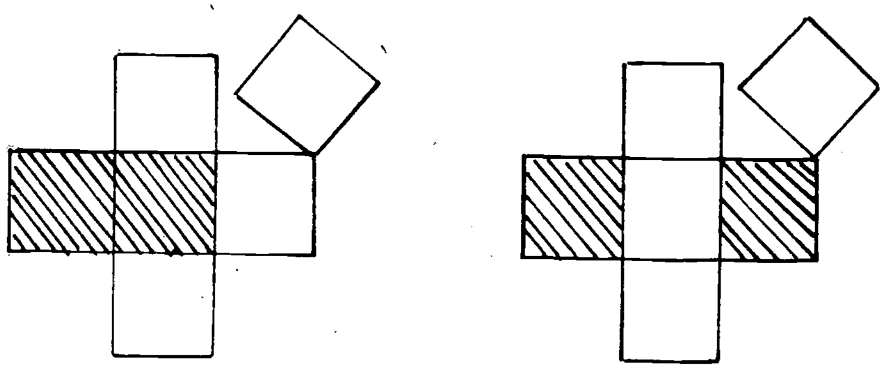
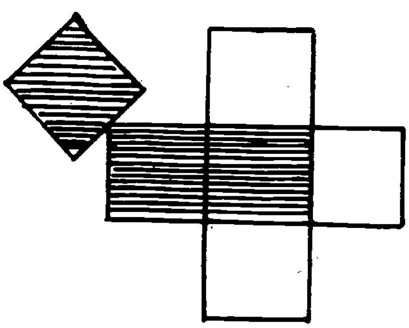


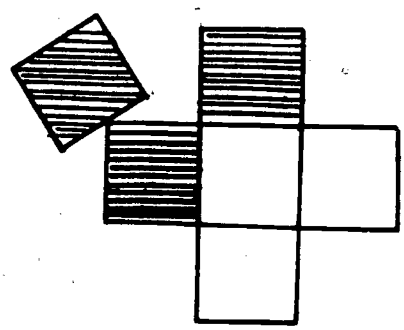
Figure 5

c. Expose two sides of object at the same time. Raise the question, "Can you distinguish between the two models shown above by viewing two sides simultaneously?" With a little thought it becomes clear that if two adjacent sides of the first model of the die shown above is viewed, one would see the following pairs of sides; black-black, black-white, and white-white. While if the second die shown above were the die in the box, black-white and white-white sides would show simultaneously but not a black-black combination. Thus, one could use the additional information obtained when viewing two sides simultaneously to distinguish between these two possible models of the die within the box.

d. As an extension, introduce the problem where the data obtained on viewing a die one side at a time show that the number of times that a black side appeared indicating, the the die contained in the box had an equal number of black and white sides. In this case how does one distinguish between the two models below both of which satisfy the data obtained on viewing one side at a time?



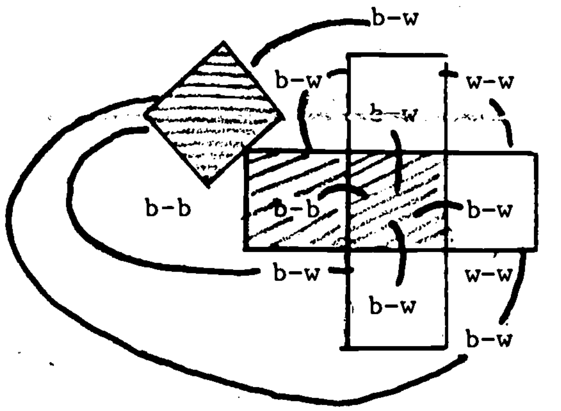
Model I



Model II

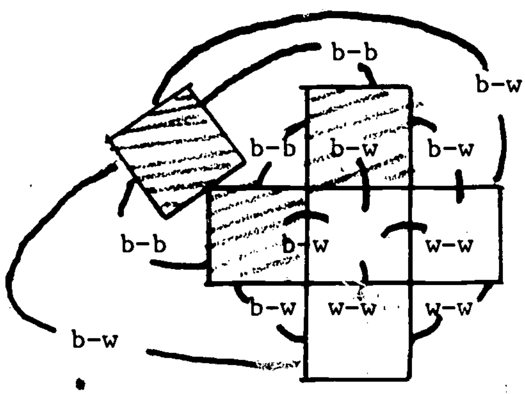
In this case both models would display black-black, black-white, as well as white-white sides simultaneously. The question is raised then, "How may one use simultaneous sightings of adjacent sides to determine which model correctly represents the die in the box?"

A little thought shows that although the same combinatic of colors appear when viewing adjacent sides of both dies, the frequency with which they appear will not be the same. This is just a more complicated version of the same problem encountered when one views only one side at a time; eith a white side or a black side was seen in either case but the frequency with which the white side showed as compared to the frequency with which the black side appeared allowed us to predict how many black sides and white sides the die in the box has.



b-b	b-w	w-w
2	8	2

Model I



b-b	b-w	w-w
3	6	3

Model II

In the figure above we indicate all the combinations of adjacent sides that can be viewed simultaneously and listed in the frequency with which they will appear on a statistical basis if two sides are viewed randomly.

Thus one can decide what model more accurately describes the die in the box by measuring the ratio of the frequency with which each of the combination of colors appear.

e. Viewing two sides of the die simultaneously, make twenty sightings and record the combination of colors that appear. Compute the ratio of the number of times the different possible color combinations are seen to occur and compare these results to the predictions above.

C. Extensions

1. Suppose in viewing one side of a die at a time concealed in a box your data showed that:

   a. Only two color faces showed, a white face or a black face

   b. The white face showed twice as often as black

   Using this data alone it is possible that the object in the box is a six sided die with two black sides and four white sides or it could be a eight sided object as shown in the figure below that rotates on its base when shaken only showing six of its eight sides.

   Show how you could use the information gained by viewing two adjacent sides at a time to distinguish between these two possibilities of correct models for the object in the box.

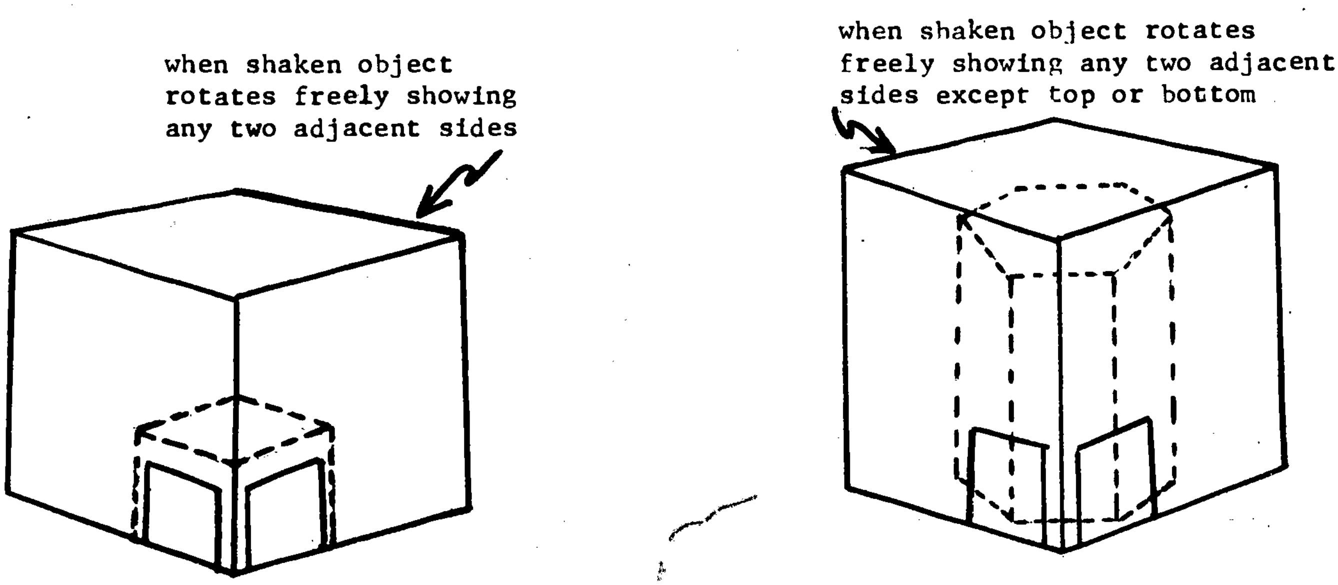
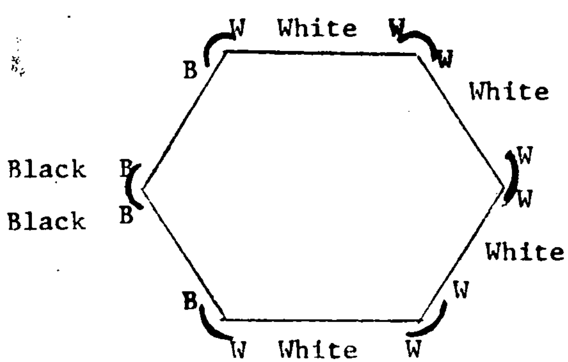


Figure 6

COMPARISON OF TWO ADJACENT SIDES
VIEWING STATISTICS
OF TWO MODELS

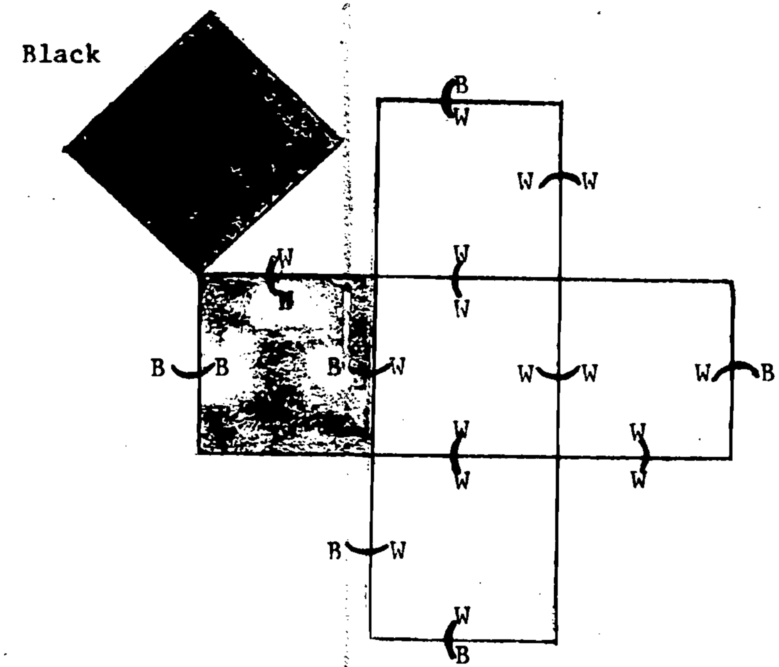
Top View of
Hexagonal Parallelepiped



Number of Distinct
Color Combinations of Adjacent
Sides

B W - 2
B B - 1
W W - 3

Flat Representation of Cube



Number of Distinct
Color Combinations of
Adjacent Sides

B W - 6
B B - 6
W W - 5

Figure 7

C, **Extensions** (continued)

2. The study of the inaccessible die is like the study of the solar system or the nucleus of atoms; they are not directly accessible. We cannot touch them but we have collected fragments of information about them. Taken as a whole those that information provides us with a "picture" of these systems.

Compare the quality of knowledge about these systems, answering the Questions:

(a) Are you absolutely sure about your model of the die?

(b) Are scientists absolutely sure about their model of the moon?

(c) After a hundred sights of adjacent sides of the die which only showed white and black faces, is it possible that the die had one red side that had never shown? Would it be "probable"?

(d) From all evidence so far the lunar sampling shows that there is no life on the moon. However, is it still possible there is life on the moon? Is it probable?

IV. SCIENTIFIC KNOWLEDGE

A. SYNOPSIS

The examples of scientific problems we have encountered so far have been chosen to illustrate the most elementary science problems, devoid of complexities. As we move closer towards problems that are more clearly representative of those that occupy modern scientists, the underlying features that give science a quality of abstraction becomes more pronounced. First, it is the nature of science to deal with an "indirect" knowledge of things if by direct knowledge one means experiencing only with the primary five human senses. Scientists use measuring instruments as extended forms of quantitatively precise senses. The world of reality is sensed through them and described in terms of their measures. Any scientific knowledge can always by reduced to inferences from the results of an experiment. This does not exclude the "experiments" of seeing, smelling, and touching performed with the "instruments" of the eye, nose, and fingers. These too we include; they simply are not instruments that give reproducible quantitative results and are used to assess data qualitatively.

As an extreme illustrative example of a problem where we seek answers in terms of indirect knowledge, the mysterious black box problem described below is offered. It provides ample grist for the consideration of the question of the nature of scientific knowledge.

B. THE MYSTERIOUS BLACK BOX

The apparatus of this experiment consists of a sealed box (old cigar box will do), several input jacks, two of which are internally connected to a battery, several switches, and a light bulb. The diagram below illustrates an example. The sealed box is then presented to the students to determine what is inside.

CIRCUIT DIAGRAM FOR BLACK BOX

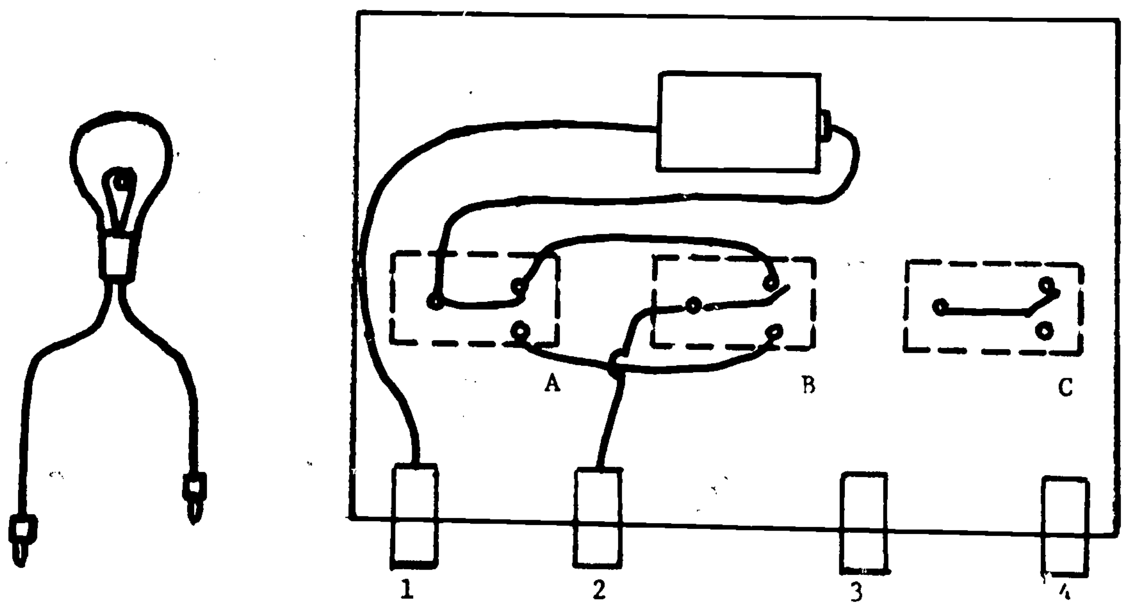


Fig. 8

1) The switches A and B are single pole, double throw (SPDT) switches, C should match them in external appearance but otherwise does not matter.

2) The lamp can be plugged into any combination of output jacks 1, 2, 3, or 4.

3) The light will light only when plugged into jacks 1 and 2, and when switch A and B are both up or both down.

4) Switch C, and jacks 3 and 4 do not respond in any way to experimentation. Consequently, with a little coaxing, the students can see that there is no scientific way of determining what is attached to these devices.

Allow several students to play with the box. (It must be a psychological law that human beings like to play with switches). In a very short time the class will have passed a very important step in the scientific thinking process. They will all be aware that there is an interesting problem to be solved. How does the black box work? What is inside the box?

Quickly the students will begin performing small experiments of their own. Which switch positions cause the bulb to light up? What patterns cause the bulb to shut off? What is the effect of plugging the light bulb in at various output jacks?

At this point the class can easily be steered into realizing that they need a convenient way of indicating switch positions and bulb positions. It is not difficult to get the class to think of using numbers or letters to designate switches and output jacks. Here, then, the class can begin to see how the development of a concise "scientific notation" greatly facilitates logical thinking.

Various students at this point might also suggest that some of their past experiences with electrical circuits might be applicable in the present situation. They might suggest a flashlight, automobile headlights, ordinary house lights, that is, anything which involves switches and objects lighting up.

Finally, the students are ready to begin to guess theories which might explain the operation of the box. Someone is sure to suggest that the switches complete the electric circuits. Perhaps, various other ideas might be suggested. Each student can then be asked to prove that his particular theory is correct. Does the theory adequately predict all the known facts in the problem? Can the student draw a wiring diagram which predicts the connection between switch patterns and a lit or unlit light bulb.

Immediately after the conclusion of this exercise a related discussion and/or a homework assignment must be given. It should be emphasized that the main purpose of the experiment was to learn about the scientific process. Discovering what was in the black box was an opportunity for involvement in that process. Any questions can be asked which lead the student toward wondering how he went about solving the problem. For example,

1) Why were you interested in discovering what was in the box?

2) Did you utilize any of your past experiences in order to find the solution? How did they help?

3) Before we opened the box were you <u>sure</u> of what was in it? Could it have been different?

4) How did you go about deciding what was in the box? What did you base your ideas on?

5) Do you think there was any set method that we used today in finding the solution?

6) Did you use your imaginations? Did you make a lot of guesses? were a lot of those guesses incorrect?

7) How were incorrect guesses (i.e., incorrect theories) proven to be incorrect?

8) Write down very carefully a summary of what we did today. Discuss, in your opinion, how what we did was like what a scientist does.

9) It has been said that the experiment illustrates very much how a scientist tackles a problem. If this is true write a short essay discussing how a scientist attacks problems.

Some of the questions are more suitable as homework exercises than as discussion material. They all tend to get the student thinking about his class experience as a process of thought.

This demonstration can always be used to begin discussions on a sophisticated level about the philosophy of science. One can begin to discuss things like:

1) What is truth? Are scientific theories absolutely true?

2) What is a good theory? Are they simple? Why couldn't some other wiring diagram be possible?

3) What sorts of phenomena in the world can science deal with? Is astrology a science? What about the switch which has no effect (Switch C)? Can science ever determine what is connected to it?

Needless to say such questions should only be asked toward the end of the course. Other more sophisticated uses of this experiment are discussed below.

This section has several advantages. First it illustrates a scientific problem from start to finish. Therefore, it gives the class insights into how a scientist tackles a problem; these insights must be re-inforced by directed questions and other future work. Second, the unit is simple enough to be understood and fascinating enough to be appreciated by non-science types.

C. EXTENSIONS

This experiment also has some interesting extensions. Suppose that after the class has completed it, the instructor alters the switch system by adding a resistor or two into the circuit. In this case with the switches in the same "lit" positions as before, some of the positionings will cause a definite dimming of the bulb. The students can be asked if their previous theory is still a good description of the phenomenon. It should be noted that the theory still explains the "bulb" properties of the problem, but some details are not accounted for. Should the theory be scrapped or modified? Scientists, of course, try to modify theories when discrepancies appear rather than totally discard them if they can. If it should be modified how can the dimming be explained? If someone proposes an idea of an object which "weakens electricity", where should it be placed in their previously developed wiring diagram? Again the students, in this case, can get a good idea of the advantages and limitations of scientific theories. Suppose at the end of the experiment, after a wiring diagram has been developed which the whole class accepts, that the instructor does not allow the device to be opened. In other words the class can only rely on indirect evidence (the lighting of the bulb) to determine whether their diagram is correct. One might ask the class: Is the "real", "correct", "truthful" explanation of what is in the box what we have decided? How do we really know that that particular circuit is in the box? Could not the truth be something other than what we have imagined? In other words a discussion can be brought in at this point which delves into the problem of what science can really decide. All scientific theories are like a model of a black box which we can never open; we must always rely on "indirect" evidence. We can, however, construct alternate sets of experiments that confirm in many different ways and in many instances the validity or usefulness of our model. After all this is the purpose of science, to construct self consistent models based on integrated theories that enable us to understand the behavior of nature. Science does not recognize truths that are inaccessible to experimentation. That's the domain of Philosophy.

This does not mean that if there is a natural law which prevents us from looking in the box, the study of the behavior of the box is not a scientific problem. It may be important to know how the switching mechanism on the box affects which light comes on and in what order. If this is the case then we become concerned with constructing a model whose predictions are consistent with our observations. But if we are asked, "How do you know what is really in the box?", implying that there is some reality that transcends measurement - remember there is a physical law which says our view of the contents of the box is restricted - the question is beyond the scope of science. "What acts as if it is in the box?" is a scientific question. "What is in the box?" becomes a philosophical question.

V. NUMERICAL PATTERNS AND MEASUREMENT

A. INTRODUCTION

Simply stated, the charge of the scientist is to seek order in the behavior patterns of natural phenomena. In so doing he relies on a rich resource of tools that are natural and useful, namely mathematics. Mathematics is an invention that is an inseparable part of man. We are mathematicians all. We deal with life and its problems with a sense of symmetry, order, and balance. It is evidenced from the houses we build to the art we produce. But for most of us this sense is a qualitative one not easily articulated or communicant; but it is there.

This sense is also a valuable endowment in science but, as a vague or qualitative sense, it has limited value. Science demands a more precise and quantitative treatment. It is in the nature of the questions we pose and the type of patterns we seek, perhaps because of the technological origin of science. Mathematics provides this precision. It is a language which insures a precise and universal meaning to our descriptions of phenomena, that our conclusions are testable and the conditions of the tests are repeatable. But more than that it is a language so deeply and naturally a part of us that it is a fertile medium for our search for patterns.

Mathematics, then, is an analytical tool. A valuable and indispensible one, but only a tool. It needs stuff on which to work. If the mathematical models we construct and the images of numerical patterns we dream have no connection to reality, what we are doing is not science. It may be a valuable intellectual enterprise but it will not be science. Science is a direct and meaningful interpretation of natural phenomena. The bridge between the world of reality and the world of mathematics is physical measurement, measurement with meter sticks, clocks, and scales. This is the stuff we knead in a search for order, the grist for study. But it too taken alone is not science. Science is both measurement and analysis.

In this section we have developed several activities which provide a concrete basis for clarification and discussion of the role and value of measurement and numerical patterns in the study of physical phenomena.

B. A HISTORICAL EXAMPLE

A classic example of the use of numerical patterns in science is the famous astronomer Kepler's use of geometry and arithmetic scrutiny to classify the regularities of the orbits of the planets of our solar system. Kepler's early attempts to order the astronomical patterns is particularly fascinating. As a young student he was captivated with the notion that the number of planets were fixed and set out to discover why. His solution was a brilliant and unusual one. A short account is given in Appendix 3.

Religion was a great influence on the early astronomers. They were awed by the "perfection" of the "heavenly" bodies. But as scientists, they were equally impressed with the "perfections" of mathematics. So it was natural that Kepler attempted to explain the order of the heavens by studying the properties of geometry. (It was not until 90 years later with the discoveries of Newton, did the principles emerge to give explanation of astronomical phenomena in terms of gravitational forces) His solution involved a purely mathematical relation between the ratio of the radii of concentric spheres inscribed inside of regular polygons with an increasing number of sides. It is a property of three dimensional geometry that there are only 5 regular, three dimensional polygons. During Kepler's time there were only 6 known planets. As astronomical chances (no pun intended) would have it, the ratio of the radii of spheres so constructed was almost exactly the same as the ratio of the orbits of the planets. This was both a stroke of luck and an unfortunately cruel joke of nature. The fact that the numbers are almost the same is an incredible accident. The reason that the ratios are as they are have little to do with the properties of geometry. (The problem of why there are only "six" planets posed by Kepler is not considered a "basic" physics problem today; for the fact that the number is what it is - namely nine - is due to the conditions of creation of our solar system.)

Kepler was disturbed by the inexactitude of the result. He spent several years of his life on a study of the precise motions of the planets but could not redeem his original idea. After 22 years he published his famous three laws on which modern astronomy is based. These three laws are also numerical descriptions; but this time his findings were obtained after studying masses of data on astronomical sightings. These laws were, however, not as symmetrical or as appealing as the first erroneous "law"; for its aesthetic appeal is almost universal. Even those who know little about science find it intriguing because of its disarming simplicity. This is an indication that there is a mathematical sense of symmetry lurking in all of us, prompting us to play with numbers and shapes imitating the patterns of nature.

Kepler's three laws were arrived at after years of painstakingly laborious study. The style and the use of mathematics used in it is quite different from that in the first theory. Yet, in both cases Kepler drew on deep resources of mathematical insight to discover these patterns so ingeniously hidden. In neither case are the patterns obvious; nor do they jump out at you after a moment's reflection; they only reveal themselves with torturous effort. Most patterns of numerical relationship among physical properties are not as difficult to find as those Kepler uncovered. In the next section there are several problems listed as exercises in forms of numerical and geometrical pattern deduction.

Questions

(a) Discuss why the basis of Kepler's first idea, namely, that one can study the properties of geometry and from that alone deduce the properties of the planetary system would not be considered sciende today.

(b) Study the statement of Kepler's three laws in appendix 4 and discuss whether Kepler's study leading to these laws may be considered science.

C. EXTENSIONS

The studies in this section are intended to provide an opportunity for students to practice searching for numerical patterns associated with the measure of quantities representing physical properties. The first set of problems are analogues of physical problems using playing cards and a slide rule. In this instance these devices represent physical apparatus with conveniently built in "meters" that generate a measure of some physical property of interest, e.g., a length, a weight, or a time interval. The analogue problem thus helps to relieve the anxieties that a student may feel about the details of precisely how a quantity is measured with real apparatus until he has developed confidence to deal with it.

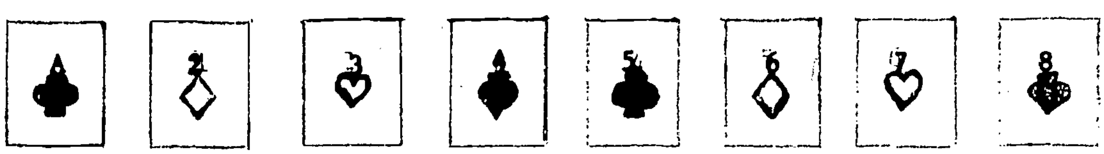
1. Patterns in Analogue Problems

a. *Card Game*

This activity has several variations. Its basic format uses several decks of identical sets of cards.

Variation I: (For two players)

i) Create a pattern with a row of cards using as many mixed decks as you need to produce the patterns that you have in mind. Consider for example, the pattern below.



ii) Remove several cards but leaving enough so that a pattern is still evident.

iii) Ask your opponent to identify the pattern.

iv) As he works on a solution, your opponent may request additional data in the form of the identity of one or more of the missing cards as a test of the correctness of his theory. Or he may simply need additional information.

v) Each player is given 50 points at the beginning of the game. Each time your opponent requests an additional card he must guess its identity on the basis of the pattern of cards showing. If he guesses correctly, he get 10 additional points; if he does not, he loses 10 points.

vi) The game is over when each player has identified (correctly or incorrectly) all the missing cards.

Variation II:

For ease in accommodating a large number of groups at one time, sketches of a sequence of cards should be drawn on a single sheet. Each sheet has a code number to which the teacher can refer when more data is requested

Variation III:

Games may be played between groups of students where they arrange the pattern for the other group to find, and simultaneously try to deduce the solution of the pattern the other group has given them. Alternate turns are taken at giving solutions or taking more "data".

Variation IV:

Instead of displaying an entire sequence of cards at one time a more difficult version is to begin with a large number of points and no information. With each card that is turned up points are lost if the student does not predict the identity of the card correctly or points are gained if he guesses correctly.

In figure 9, we have given several card arrangements as suggestions.

SOME SUGGESTED SEQUENCES
for
"CARD PATTERNS"

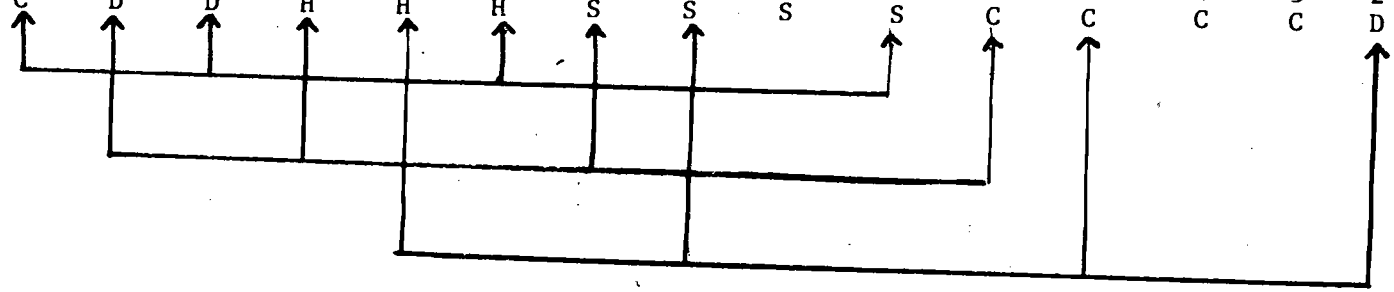
I. A 2 3 4 5 6 7 8 9 10 J Q K

II.

A	2	2	3	3	3	4	4	4	4	5	6	6	7	7	7
C	D	D	H	H	H	S	S	S	S	C	D	D	H	H	H

III.

A	2	A	2	3	A	2	3	4	A	2	3	4	5	2	3	4	5
C	D	D	H	H	H	S	S	S	S	C	C	C	C	D	D	D	D



Hint for III:

Note permutation of
suit arrangement CDHS,
DHSC, HSCD, etc.

Fig. 9

b. *Geometric Patterns*

This exercise is similar to the one above except geometrical figures are used in place of the cards. With this variation in the game, there is a greater flexibility in what features of the objects are to be compared and ordered. Several modifications of this game are possible as long as the essential rules remain the same:

i) There is a sequence or pattern of arrangement of the objects that is to be guessed by the other.

ii) After the pattern is established, some of the objects are removed so that the person trying to find the pattern may test his solution by predicting features of the missing figure.

iii) Because comparing geometric figures is more complex than comparing cards, there is an additional rule. There may be several properties of the cards that may be useful, but give only partial non-unique solutions. For example, if there is a pattern to the shapes of the components of a figure that can be predicted, this should be given credit, even if the total solution requires knowing how these figures are connected.

As an example of this version of the game of "squares", we have created a sequence of geometrical shapes shown in figure 10. There are two properties that we have arranged in an order in this figure. The simplest ordering of the figures is according to the number of intersections appearing first in the arrangement. All possible variations of singly overlapping triangles that produce 2, 4, and 6 intersections are displayed. This is one feature of the ordering, but only a partial solution. With this alone, one still does not have a unique pattern, i.e., it would give us no unique way of ordering the figures with the same number of intersections. We have provided for this in arranging the figures in order of increasing periphery of the areas of overlap. If one wants to add a numerical quality to the pattern, the value of the peripheries of the overlap areas could be arranged to be increasing integral multiples of one another.

A SEQUENCE for GEOMETRICAL PATTERNS

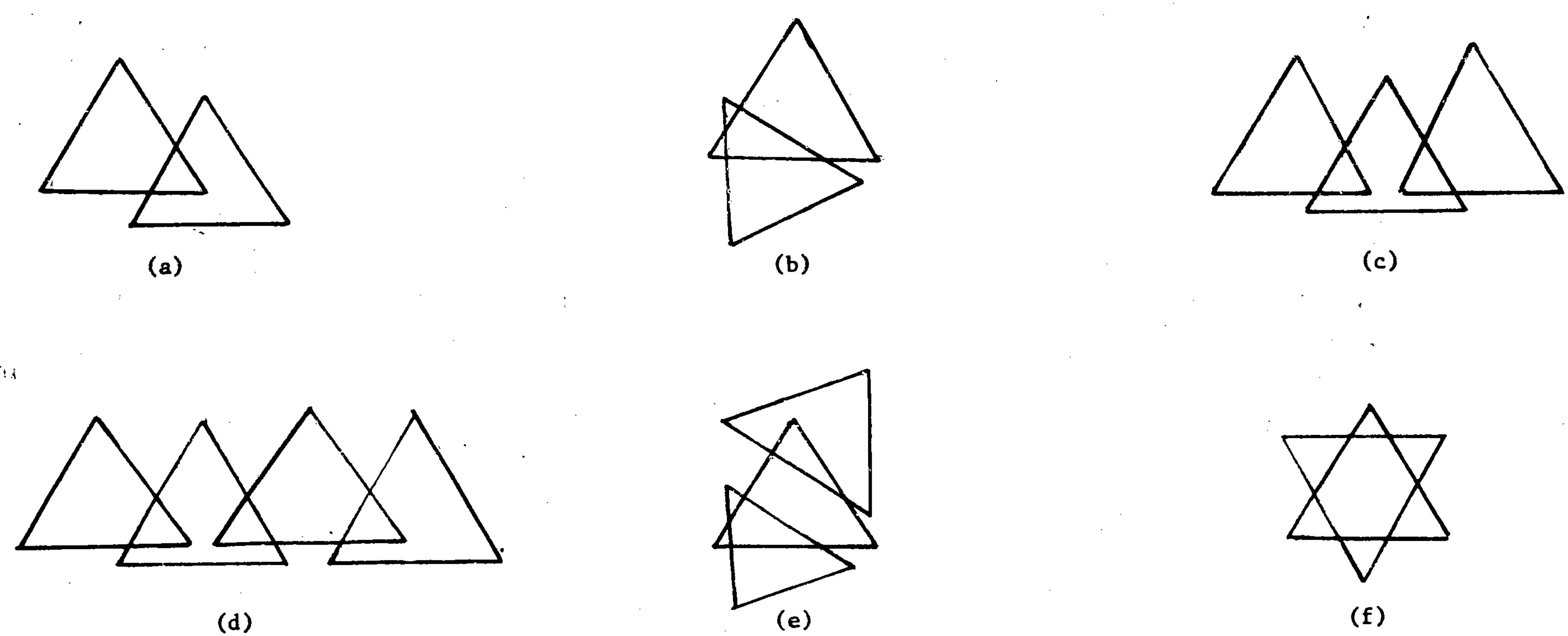


Fig. 10

A Solution

Ordering by number of intersections: a; (b, c); (d, e, f) where there is no ordering among the figures whose letters are given within the brackets

Ordering by increasing sum of peripheries of overlapping area: a, b, c, d, e, f

c. *The Slide Rule as a Number Generator*

In this exercise, the slide rule may be considered to be a "measuring" instrument where the numbers on its scales represent some physical property. Comparing the numbers on adjacent scales will be analogous to comparing numbers on instruments that measure some physical properties. Our problem is to find a relationship between the numbers on adjacent scales and to express it mathematically.

This exercise has an advantage over those above. Once a relationship is empirically discovered by comparing a set of numbers, it may be checked to see if it is also valid for an even larger class of number chosen at the discretion of the experimenter, i.e. he may test his law under new experimental conditions of his own choosing.

i) *Relation between the D and A scales:*

As a first step, it is important to have students decide precisely how they are going to record their data. Most choose to record their data in two column tabular fc m, with adjacent numbers on the D and A scales recorded on the same row.

As the numbers are being read off the slide rule, it may occur to some students that they are not sure where the decimal place goes in the numbers they are reading. They should make a guess and proceed.

The students are instructed to collect pairs of numbers adjacent on the scales until there is enough data that suggest a pattern to them. Patterns that may fit their data are constructed by generating rules that allow them to obtain one set of numbers from the other. For example, if 2 and 4 are a pair of numbers to be related, possible relations are $2 + 2 = 4$, $2 \times 2 = 4$, $2^2 = 4$, etc. These relations are then to be tried on other pairs of numbers until all the incorrect ones are eliminated. Once a law has been obtained that correctly relates all numbers he has obtained from the scale, he should try to use his law to predict a number adjacent to one he has not tried yet, thus, checking the validity of his law to be extended to more general circumstances. In this way the basic relation $D^2 = A$ may be empirically deduced, where D and A represent the adjacent numbers on the D and A scale respectively.

ii) *Relation between the D and K scale:*

The relation between the D and K scales should be obtained above and found to be $D^3 = K$.

iii) *Extensions to use of the relations found above:*

Encourage students to use their laws and new circumstances and then check them. For example, use these laws and the rule to find $\sqrt{20}$ and $\sqrt[3]{5.8}$, then <u>prove</u> that their slide rule obeys the law by squaring the number found to be $\sqrt{20}$ and comparing it with 20, similarly cubing the number supposedly equal to $\sqrt[3]{5.8}$, cubing it, and comparing it with 5.8 .

iv) *Relation between the K and L Scales:*

At the outset of this experiment it is necessary to discuss the importance of considering experimental error whenever making measurements. The idea is easily extended to reading of the scales on the slide rule. How accurately can these results be read? It is clear that there is some inaccuracy in his readings. For the purpose of this experiment we shall assume the error is 5%. Students will agree that it is a reasonable estimate.

It is necessary to make this consideration especially when studying these scales because, there is a fortuitous, approximate, yet appealingly simple relationship between the adjacent numbers on these scales that one is led to postulate if one believes that the scales contain an approximate 5% error. For example, the numbers on the K scale opposite 0, 0.1, and 0.2 on the L scale are 1, 2, and 4 respectively. This data is taken with the same assurance as that taken for the other scales. However, for larger numbers on the L scale, the apparent relation of doubling the numbers on the K scale as we increase the numbers on the L scale by 0.1 is only approximately valid only if we assume an approximate 2% error in the readings on the K scale up to values of $L = 1.0$. The relation is so simple and attractive that we assume it must be right. Surely it could be no accident.

As an exercise ask that this relation be expressed in equation form. Thus, we arrive at the result $2^{10L} = K$.

v) *Extension of the Relation between the K and L scale:*

This exercise is recommended for only those students with a facility for mathematics, as they will be required to manipulate transcendental equations. However, the results and the conclusions may be profitably shared with the students who are not mathematically inclined by a class report at the end of the experiment.

After having arrived at the empirical law $2^{10L} = K$ above, we have an obligation to check the validity of our law. One kind of such check is to see if this result is consistent with the other laws that we hold to be true. We may then check this law with the law $D^3 = K$ if we had a relation between the D and L scales we could eliminate D in these two equations and derive a relation between the K and L scales. We provide students with the relation $\text{Log}_{10}D = L$ by postulating it.

Exercises

ai) Verify that the relation $\text{Log}_{10}D = L$ is correct by checking a book of tables with the values for logarithms.

aii) Using the relation $\text{Log}_{10}D = L$ and $D^3 = K$, derive the relation $10^{3L} = K$.

The result of this calculation yields $10^{3L} = K$ which is obviously in conflict with the empirical relationship. But if we check the validity of the deduced relationship for the values of L and K used in finding the empirical relation, we find the "theoretical" law is also valid within the limit of 5% accuracy. Thus, we have two different mathematical relationships that cannot be distinguished between if we have error bars of 5%. We need more accurate measurements of the phenomena that they may represent to distinguish between them and choose one or a better representation than the other. Or extend our measurement to cases where the differences between the two laws is more than 5%.

To underscore these similarities of the two laws within 5% inaccuracy we have plotted the results of the two laws for two ranges of the values of L and K with 5% error bars in figure 11. Significant differences between the two laws are apparent only for large values of L, as shown in figure 12.

MATHEMATICAL RELATIONSHIP BETWEEN ADJACENT NUMBERS ON THE L AND K SCALE ON THE SLIDE RULE

Value L scale	Read on K scale	Value Predicted by Relation K_t	Relation, K_e
0	1	1	1
0.1	1.98	2.00	2
0.2	3.96	3.94	4
0.3	7.9	7.88	8
0.4	15.8	16.2	16
0.5	31.5	31.6	32
0.6	63	63.0	64

Note: Both sets of theoretical Relations K_t, and K_e fall within 5% error bars on experimental data.

Hence, we cannot distinguish between these two mathematical relationships as correct trends based on this data.

Where

$K_t=10^{3L}$, (Theoretical Law)

$K_e=2^{10L}$, (Empirical Law)

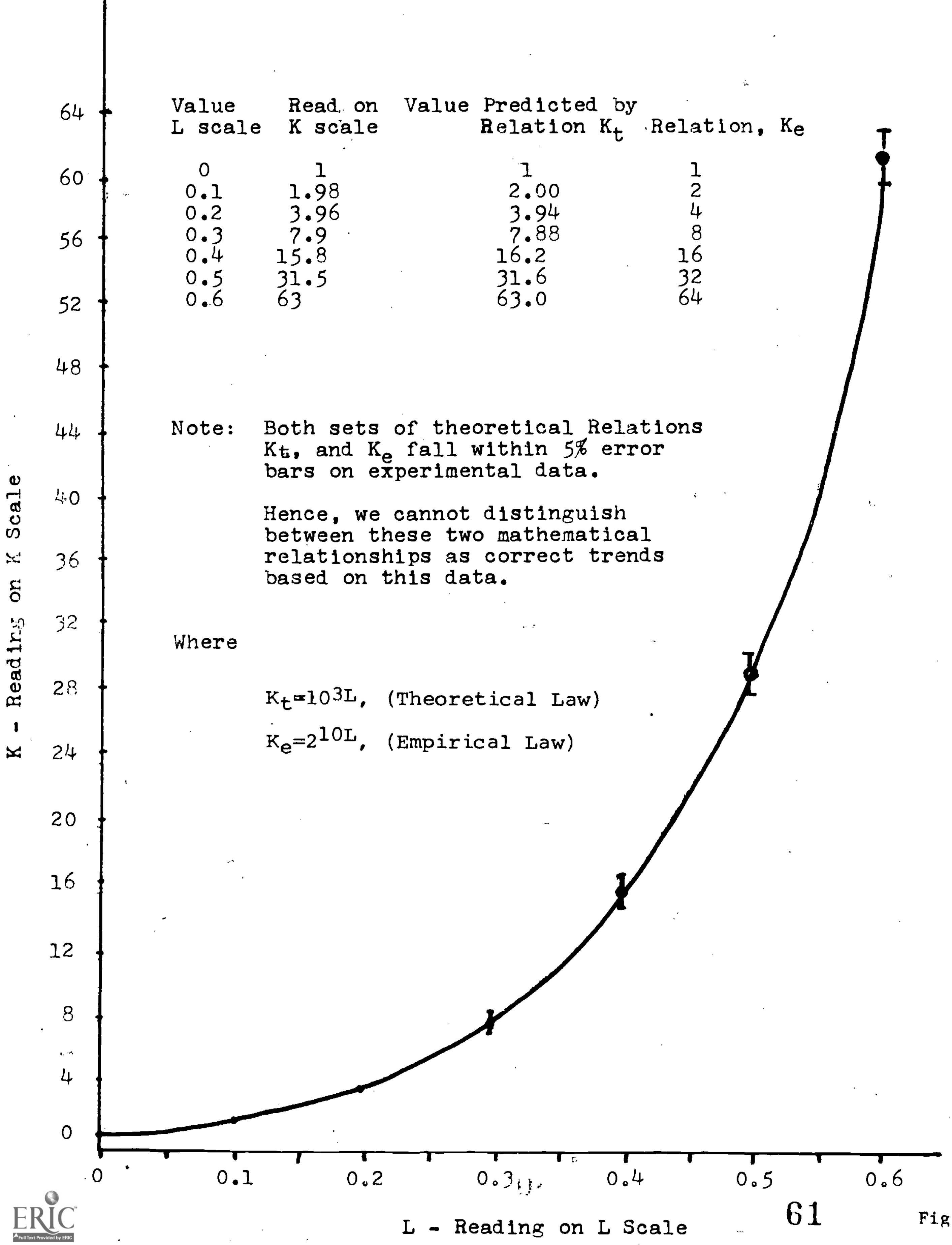
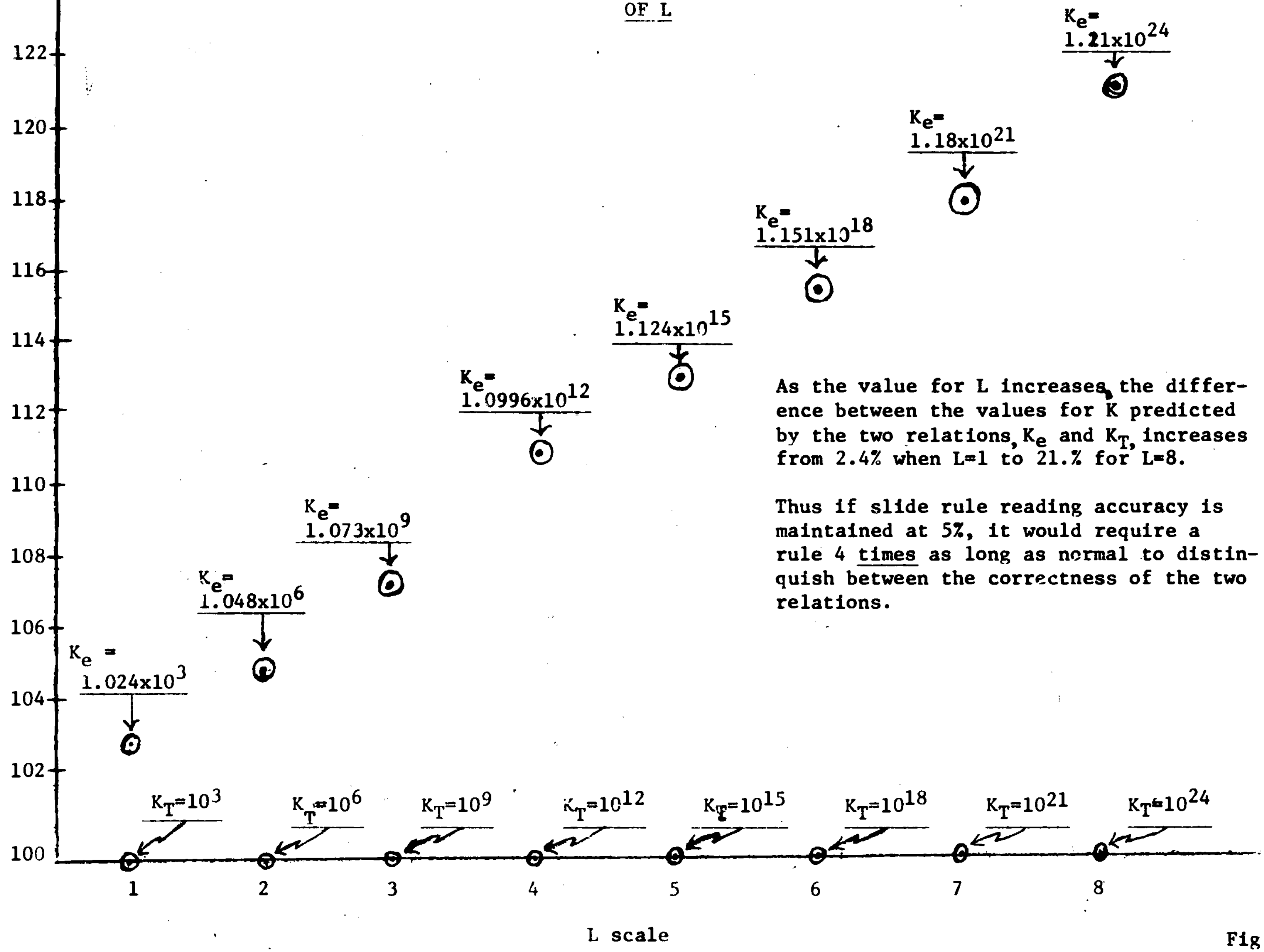


Fig. 11

COMPARISON OF THE RELATIONS
K_T AND K_e FOR LARGE VALUES
OF L



As the value for L increases, the difference between the values for K predicted by the two relations, K_e and K_T, increases from 2.4% when L=1 to 21.% for L=8.

Thus if slide rule reading accuracy is maintained at 5%, it would require a rule 4 times as long as normal to distinquish between the correctness of the two relations.

Fig. 12

2. Numerical Patterns in Physical Problems

In the following problems we extend our use of the techniques used in the previous analogue problem to real physical problems -

a. *The Simple Pendulum*

A set of pendulums are made available for students to study. The set consists of several simple pendulums with identical "bobs" with the length of the supporting string varying as well as several of the same length but with weights so obviously different they can be distinguished easily by feel. The purpose of the experiment is to study some physical property of a system that can be easily measured with a meter stick, stop watch or force scale, for example, and that displays a simple numerical or mathematical relationship easily detected. During the study, the values of a numerical description of the relation between the properties studied will be analyzed and its advantages over more qualitative studies pointed out.

At the outset of the experiment the students should be divided into small study groups and each instructed to make a comparative study of their set of pendulums in order to deduce some useful law of behavior for swinging pendulums, such as the relation between the period of oscillation and other properties of the pendulum. So stated, the problem is sufficiently general to be open to many approaches, yet sufficiently specific, that students should feel that the experiment has a direction.

As a motivation for studying this problem, several examples of the use of hanging objects in engineering or science problems should be cited and the value of understanding the principles of their behavior, such as pendulum clocks or suspension bridges, etc. It should also be readily admitted that the pendulum system was chosen to study because it is simple and a rich resource for problems.

The first stage of the investigation should be a qualitative study that will be useful in shaping a more detailed study. Students should be helped to organize their study by asking them to list properties of the swinging pendulum that may be worth studying. In this way a number of possibilities are generated, including weight, size, length, displacement, etc. Students should then compare pendulums with different properties and note the difference in the behavior. For example, pendulums that have different lengths but are otherwise identical, swing at different frequencies. Finally, for ease of analysis these statements may be translated into statements about a single pendulum with variable properties, such as:

(i) As l (the length) increases, T (the period of oscillation) increases.

(ii) As d (the horizontal) displacement increases, T is unchanged.

(iii) As W (the weight of the object) increases, T is unchanged.

(iv) Etc.

Such a set of data constitutes a good qualitative description of a system. Information such as this can be shown to be useful, informative, and even enlightening. Several of these relationships are surprising and could not have been anticipated. Others are obvious and clear from our everyday experience.

In order to obtain sufficient information for a comparison between the above type of study and a quantitative one, we move to the next part of the experiment. One of the qualitative relationships found in the first part of the study should be used as a subject for a more detailed quantitative study, for example, the relation between T and ∝ ℓ . Instruct the students to measure the period of oscillation and the length of the pendulum for six to ten different values of each. Stop watch time interval and centimeter length accuracy will suffice. A table similar to the following is thus obtained by each group:

Table I

ℓ	10cm	20cm	30cm	40cm	50cm	60cm
T	.63 sec.	.90 sec.	1.1 sec.	1.26 sec.	1.4 sec.	1.55 sec.

On the face of it this data is of little more value than the qualitative description, except there is more of it. The advantage of a quantitative measure of the properties of a system lie in the precision of their projected predictions about untried conditions of the system. For example, if we ask:

(i) What is the period of oscillation of a pendulum 70cm in length and

(ii) What is the period of oscillation of a pendulum 35cm in length, using our qualitative analysis, we could answer only, (i) it is between 1.1 sec. and 1.25 sec., respectively. But using this data and mathematical techniques we can give precise answers.

The use of a mathematical analysis assumes that the results we observe are a part of a more general pattern that may be obtained by an extension of these results. But the extensions must contain the flavor or trend of the behavior we have noted. In tabular form we have no method of obtaining precise answers to the questions above, but we can translate the

the question nicely into a problem of graphical or pictorial extensions. We begin translating the data shown in table I into graphical form as shown in figure 13. An answer to question (i) requires extension to the conditions beyond those already observed by drawing a smooth curve through all of the points that represents the behavior of the pendulum and extending the curve "in like fashion" beyond the points of data. In this way we may project predictions of the behavior of the system in a fashion "like" that of previous behavior. The numerical values of the conditions sought we indicated on the figure 13.

Clearly there is some arbitrariness to the kind of smooth curve we draw through the data points, but it gives us an answer that is more precise than the qualitative results.

A representation more exact than graphical extensions may be obtained if we appeal to mathematical extensions. Using the same beliefs that motivated us to draw smooth curves between data points, we may ask, "what is the simplest mathematical expression that represents a smooth curve between the data points?" and use the resulting formula as mathematical representation of the relationship between T and ℓ. For the data used, $T^2 \propto \ell$ is appropriate.

Procedure

(i) Using the table of data that you constructed similar to table I, predict the period of oscillation for a pendulum 5cm longer than the longest you have tried.

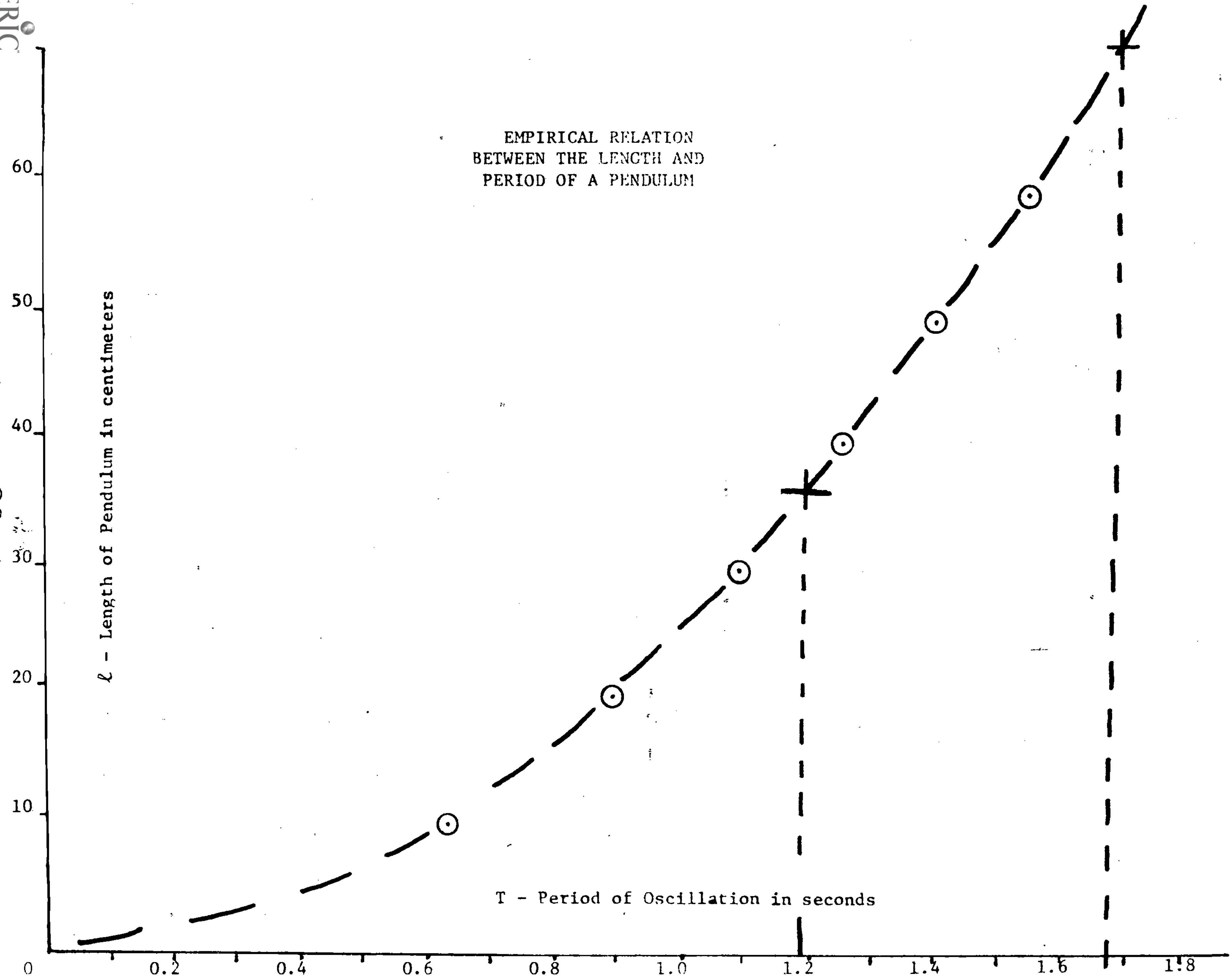
(ii) Plot the values of your measurements of the length of the pendulum, l, and its period of oscillation.

(iii) Draw a smooth even flowing curve through the points on your plot. Continue this curve beyond the points representing your data.
Using this curve to define a relationship between the length of the pendulum and the period of its oscillation predict the period of oscillation for a pendulum 5cm longer than the longest you have tried.

(iv) Construct a pendulum whose length is 5cm longer than the longest you have tried so far. Measure its period of oscillation. Compare this value with the values obtained from the table and from the plot

(v) Repeat this experiment for a pendulum whose length is between the length of two whose period you have measured and recorded in your table. Predict the period of this pendulum using the data in the table above and then by using the curve in your graphical plot. Finally, construct a pendulum of this length and measure its period. Compare this value to the other two predictions.

(vi) Discuss the relative merits of the qualitative study and the quantitative study.


EMPIRICAL RELATION
BETWEEN THE LENGTH AND
PERIOD OF A PENDULUM
ℓ - Length of Pendulum in centimeters
T - Period of Oscillation in seconds
60
50
40
30
20
10
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

One of the advantages of a mathematical description of a system is its value in capturing the universal aspects of behavior of a class of systems. For example, the description of the pendulum we have obtained above is independent of the shape or size of the object used to obtain the data. Thus, the mathematical model that we have created is potentially more widely usable as a accurate description of other swinging systems. It may, for example, prove a valid model for freely hanging cylinders.

Problem:

(i) Check whether the relation between the length of the pendulum and its period of oscillation expressed as $T^2 \propto \ell$ is valid for freely swinging cylindrical pendulums. Obtain several cylinders of various lengths - ideally a variation of length from two to five times the smallest should be used - and experimentally compare their lengths and periods of oscillation to the theoretical relation of $T^2 \propto \ell$.

b. *The Simple Lever*

A simple lever system is another physical system that may be profitably studied to gain insights into the advantages of quantitative measurements. An inexpensive and easily obtainable system may be composed of a yardstick as a lever arm, a system of small standard weights from a two pan balance system and a sturdy fulcrum.

Using a justification similar to that for the pendulum problem for this study, namely that it is a good representative problem of the larger class of real physical problems that are studied in physical science, instruct students to study the lever system, first qualitatively and then quantitatively.

Procedure

Qualitative Study

(i) Using two weights only, not necessarily the same value, find as many different relations between the position of the weights and the balanced condition of the system as you can.

(ii) Using one weight in a fixed position on one side of the lever find qualitatively where different weights must be placed on the other side, one at a time, to achieve the balanced condition.

(iii) Construct qualitative laws describing your results.

Quantitative Study

(iv) Make measurements of four conditions under which a balanced is achieved using two fixed weights. Record the value of the weights and their distances from the center support.

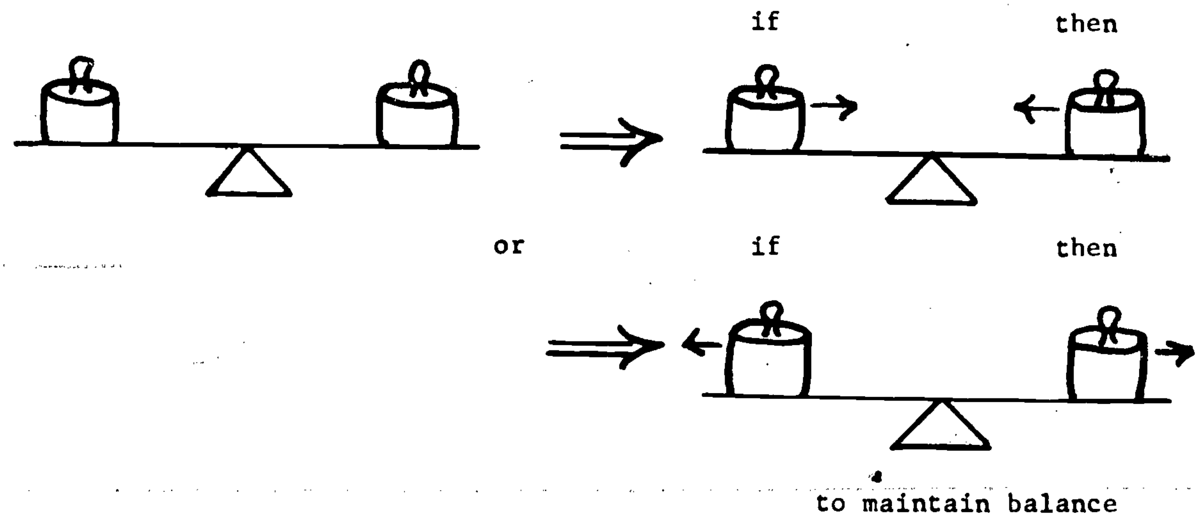
(v) After you have constructed a table containing the distances for two objects in four balanced positions, move one object to a new position. On the basis of the data in your table alone, predict where the other object must be placed to regain a balanced condition.

Plot on a graph the distances of one object from the center support versus the distance of the other object from the center support during balanced conditions. Using the graph, predict where one object must be when the position of the other is fixed as described above.

Finally, experimentally determine where the other weight must be if the balanced condition is to be regained. Measure the distance of the second weight from the center support and compare this value with the two predicted values.

Pictorially

1.



2.

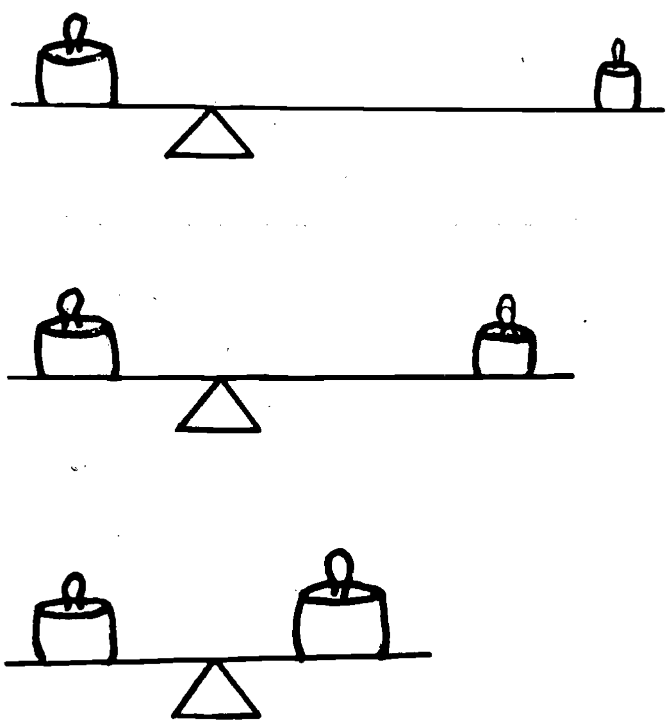


Fig. 14

Verbally

1. Given two weights not necessarily the same, there are numerous balanced positions.

   (b) Once a balanced position is obtained, if one weight is moved in or out from the fulcrum the other must be moved in or out as well, if the balanced condition is to be maintained.

2. (a) If a balanced condition is obtained for two weights and one is replaced by a lighter weight, the balanced position of the new weight is further from the fulcrum.

   (b) If a balanced condition is obtained for two weights and one is replaced by a heavier weight, the balanced position of the new weight is closer to the fulcrum.

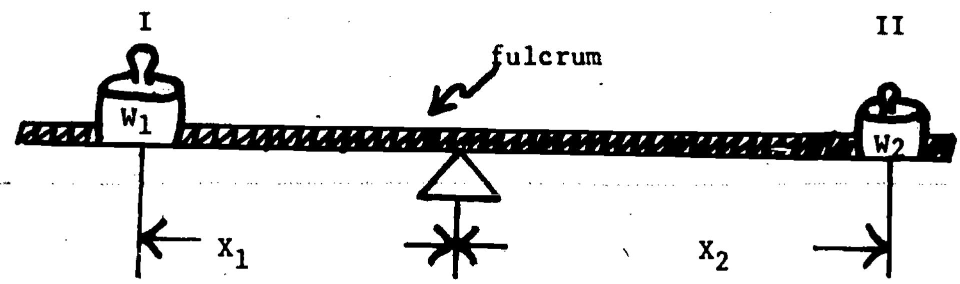
As in the problem dealing with the pendulum this is a useful description, but it is lacking precision. Instruct the students to make a quantitative study, this time measuring and recording the value of the weights and the position under balanced conditions. As a consequent, groups will generate data tables similar to that shown in figure 15.

LEVER STUDY

Balanced condition with two weights with varying position

Value of Weight I = 300gms.; value of Weight II = 100 gms.

X_1	5cm	10cm	15cm	20cm
X_2	15cm	30cm	45cm	60cm



Balanced condition with one weight fixed (W_1) varying position and weight of W_2

Value of Weight I = 300gm; X_1 = 10cm

X_2		30cm	60cm	15cm
Weight II		100gm	50gm	200gm

Fig. 15

Problems:

Using the data generated in figure 15, and graphical techniques of extrapolation and interpolation, predict:

(i) The necessary position of X_2 for a balanced condition if W_I = 300 gms, W_{II} = 100 gms, and X_1 = 24cm.

(ii) The necessary position of X_2 for a balanced condition of W_I= 300gms. W_{II}= 100gms. and X_1 = 12.5cm.

(iii) The necessary position of X_2 for a balanced condition of W_I = 300gms., X_1 = 10cm, and W_{II} = 150gms.

(iv) The necessary position of X_2 for a balanced condition of W_I = 300gms, X_1 = 10cm, and W_{II} = 75gms.

(v) Try to find a mathematical relation among the quantities W_I, W_{II} X_I, and X_2 as suggested by the "trend" of the data.

Hint: Try simple relations like:

$$W_I \times W_{II} = X_1 \quad X_1 \times X_2$$

or

$$W_I / X_I = W_{II} / X_{II} \quad \text{etc.}$$

C. *A Comparison of the studies of the Lever and the Pendulum*

Questions:

(i) What was the difference in the two solutions obtained in these problems?

(ii) What solution contains more information?

(iii) What was the usefulness of making measurements?

d. *Connecting the Results to Other Principles*

At the end of the experiments on real phenomena it is a natural reaction for the students to search for a more fundamental understanding of their results, asking "why" is the period of oscillation of the pendulum related to its length the way it is or "why" different weight objects balance as they do on opposite sides of the fulcrum of a lever. The question does not arise for the analogue problems because it is clear they are isolated exercises or artifical constructs. Trying new information and insights to the rest of what one knows is a natural instinct, a tendency of the layman and professional scientist alike. Only the degree of logical rigor and the methods used in making the connections differ for each. When a layman asks "why" there are rarely narrow constraints on the quality of an acceptable answer. Often an answer that indicates the degree of difficulty of a solution or one that identifies a fundamental principle that is operative is acceptable as a useful though loose connection. Scientists make more stringent demands on the quality and nature of their connections. For it is an integral part of the structure and practice of science that connections between our discoveries of natural phenomena be sought that are logically rigorous and that our models constructed taken as a whole form logically self consistent structures. As an example consider the question of why the period of oscillation of the pendulum is observed to be independent of the weight (or mass) of the pendulum bob and dependent on its length. We can construct two different levels of "answers". First we will construct a mathematically rigorous answer to satisfy the scientist who is versed in the principles of basic physics and calculus and from this extract a less rigorous answer. The point in displaying the mathematical solutions here is not to prove the legitimacy of these connections but to display the ingredients, character and structure of this kind of "answer". An appreciation of these points will not require an understanding of the equations used only an ability to identify the constituent components of the solution.

The mathematical solution displayed in figure 16 involves a use of several areas of mathematics but only two physical principles. Closer inspection shows that even the physical principle in step 1 is only another form or special case of the principle used in step 3. Hence, the only physical principle used is Newton's second law and the fact that the weight of an object may be expressed as its mass times the acceleration of a freely falling object. But the latter is also a consequence of Newton's 2nd Law. Consequently, we may say that the result that $T^2 \propto \ell$ is a logical (mathematical) consequence of Newton's second law applied to objects freely swinging at small angles.

The statement is not very exciting for most of us; it has all the appeal of a gigantic non-sequitor; or we feel like Dr. Watson after Sherlock Holmes has announced one of his brilliant solutions without giving the details. This is one of the strengths of the use of mathematics to make connections that are inaccessible to our everyday sense of order and intuition. By using the mathematics indicated above we have arrived at an answer we could not have otherwise anticipated. Moreover, this solution is rigorous, and will be universally agreed on as correct by anyone versed in the techniques used to find the answer.

Even so, once having obtained the answer this way we are without insight unless we reflect on the role of the physical principles used in obtaining the solution. If we reach into the heart of the solution and inspect the crucial features of the physical principles involved we can construct a simpler version using hindsight and analogies. Essentially what we have done is to take a system (the bob) which is freely swinging in a two dimensional plane - it "falls" periodically under its own weight and it is repeatedly "raised" from its vertical hanging position - and analyze only the horizontal component of this motion. Such an analysis plus the use of an analogy enables us to understand why the resultant motion is independent of the mass of the bob. The problem as analyzed above is similar to a ball rolling down a frictionless inclined plane, where the tendency of the ball to fall is translated into some horizontal motion. In that case too, which is much simpler, the acceleration of the motion is independent of its mass but dependent on the angle of the incline.

Thus, we are able to construct our second "answer", namely that a swinging pendulum is like a ball rolling between two inclined planes as shown in figure 17. The fact that the motion of a pendulum is independent of its mass is similar to the reasons that the motion of the rolling ball on the incline is independent of its mass, namely all masses fall at the same acceleration and the horizontal component of this motion has the same property. The fact that the period depends on the length is related to the fact that the period of oscillation of the ball rolling on the incline.

This latter argument is not as logically tight nor would one find a universal agreement to the analogies. But it is qualitatively "correct". In both solutions however, there is an appeal to some more basic or fundamental law. The quality of the non-mathematical answer is appealing because it is simpler and because it is suggestive. We are able to use it in making further more intuitive connections with our experience. But it only has a value when it is based on a logically substantial argument that will bare the weight of exhaustive critical inspection.

Answers to apparently innocent questions of why the results of an experiment are as they are, are not always so complicated nor do they always lead us through a labyrinth of mathematical logic. It all depends on how far we are from the "basic" principles in terms of which we want an answer. In the case of the law of levers that we found, the answer to why the weights balance as they do has a simple form, namely, "because that's the way it is". That is, in this case we have observed a fundamental law; it cannot be dissected into anything simpler; it is a one of fundamental starting points on which we base our knowledge of physics.

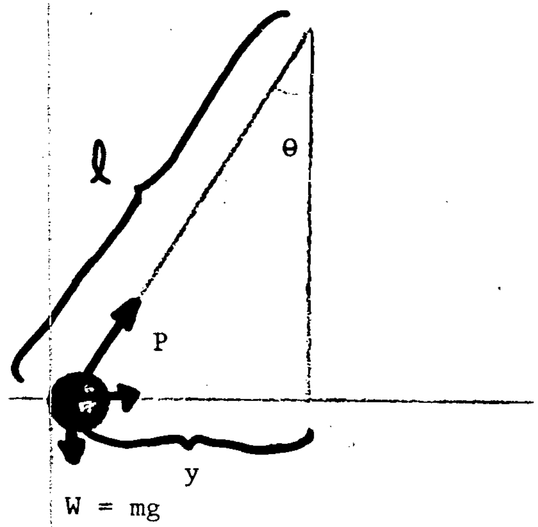


Diagram of the Swinging Pendulum:

The arrows drawn on the bob represent forces acting on it, W is its weight and P is the pull of the pendulum support.

Diagram of the structure of Logically Deducing A Relation between the period of the oscillation of the pendulum and other parameters of the system.

Logical Step No.	Description	Origin
1	Restricting analysis to oscillations with small angles, θ, we may neglect the vertical motion of the pendulum and approximate the vertical forces as being balanced. $mg = P \cos \theta$	Physical Principle (If an object is at rest the forces acting on it are balanced.)

Fig. 16(a)

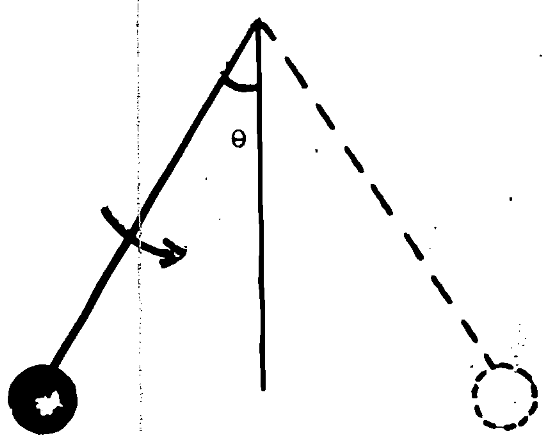
Logical Step No.	Description	Origin
2.	For small angles, θ, cos θ = 1, thus, we may further approximate the above relation by $$mg = P$$	Mathematical Relation (Trigonometry)
3.	Write the equation that describes the relation between the horizontal forces on the bob and its horizontal motion. $$F = m \times a$$ Where $$F = P \sin \theta;\ a = \frac{d^2y}{dt^2}$$ Or $$\boxed{P \sin \theta = M \frac{d^2y}{dt^2}}$$	Physical Principle (Newton's 2nd Law) + Mathematical Notation (Calculus)
4.	Relate sin θ appearing in the above equation to the parameters of the bob. $$y/_{\ell} = \sin \theta$$	Mathematical Relation (Trigonometry)
5.	Combine relation 3 and 4 to form a new relation. $$P(y/_{\ell}) = m \frac{d^2y}{dt^2}$$	Mathematical Relation (Algebra)
6.	Use knowledge of mathematics to solve the above equation relating the horizontal position, y, of the bob to time, t. $$y = \sin 2\pi t/_T$$ where T = period of oscillation	Mathematical Relation (Calculus)

Fig. 16(b)

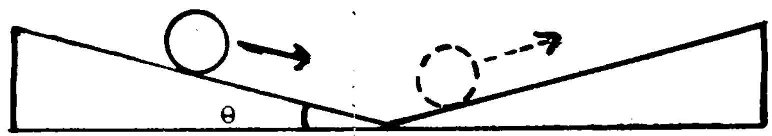
Logical Step No.	Description	Origin
7.	Use the form of the general solution to the differential equation in Step No. 6 in the equation in Step No. 5 so that T can be related to the parameter in the differential equation $$-P\left(\frac{\sin 2\pi t/T}{\ell}\right) = m\frac{d^2(\sin 2\pi t/T)}{dt^2}$$ Or $$-P\left(\frac{\sin 2\pi t/T}{\ell}\right) = -m\left(\frac{2\pi}{T}\right)^2 \quad \sin 2 \quad t/T$$ Hence $$\boxed{\frac{P}{\ell} = m\left(\frac{2\pi}{T}\right)^2}$$	Mathematical Relation (Caleulus)
8.	Substitute relation in Step No. 2 into final equation in Step No. 7 $$\frac{mg}{\ell} = m\left(\frac{2\pi}{T}\right)^2$$ Or $$\boxed{T^2 = 4 \quad 2\pi \frac{\ell}{g}}$$	Mathematical Relation (Algebra)

Fig. 16(c)

ANALOGOUS PROBLEMS



oscillating pendulum bob



oscillating ball rolling valley double incline

These two systems have similar horizontal motion for small angles. In each, the horizontal component of acceleration is independent of the mass of the object.

Fig. 17

VI. A SUMMARY

A. SYNOPSIS

Upon completing several sections of this unit on the nature of physical science, students are ready to probe their experience, adding a very deliberate thinking about the structure of science to their practice of it. By then they will have gained a working knowledge of what science is about, as they have participated in the process several times. It becomes timely to enhance these experiences pulling them together, taking stock of the anatomy of the subject, their involvement in it, and their reactions to it.

B. THE SCIENTIFIC METHOD

Although we have outlined and described several scientific studies in the preceding sections, we have refrained from listing the major components of the scientific method as a procedural guide so as to encourage students to develop their own style of investigation without heavy suggestive influence. It would, however, be appropriate to construct that list here for the purpose of a comparison with the methods that they developed. Below is a brief summary of the principle features of a scientific study.

a) Sensing the Problem - As a first stage every scientist senses the problem as a vaguely defined challenge. He becomes fascinated and is motivated to pursue it further.

b) Defining the Problem - He mulls over his impressions,re-examines the situation until he can construct a precise statement of a problem. Perhaps not at first the one that he had the original notion about. This is a valuable step in ordering his thoughts on the study.

c) Designing an Experiment - This is a stage of deliberate and ordered planning where the researcher designs and carries out a course of action.

d) Search for Pattern - In this stage the researcher attempts to form a solution to his problem. If the search is for a general law that prevails throughout a class of phenomena, then he searches for the general features that underlies all of the experiments and attempts to state it simply in the form of a general law. If he is searching for an explanation of a phenomenon in terms of well known laws, then he trys to establish the connection by forming a hypothesis.

e) Test for the Validity of the Results - As a final stage in the confirmation of a solution to a problem, the researcher must extend his test to include new circumstances that show that his answer is correct and not an accidental matching of a model to reality.

The features are not an exhaustive listing of the possible steps or stages of a scientific study; but they are representative of the major features that are found in most. It must also be pointed out that the order of these features as listed above taken as a whole represents only on ideal procedure. In actual practice the sequence and frequency with which these features occur vary with the style and insights of the individual researcher. The process of creation is a scientific study, just like that in any other creative human endeavor such as music or art cannot be wholly anticipated.

Questions

For each of the investigations you carried out in preceding sections:

(a) Identify those features listed above that also occurred in your studies.

(b) Identify those features or stages that were found in your studies but are not listed above.

(c) Construct a diagram that shows the order and frequency of occurrence of things that represent each of your studies.

(d) Using the diagram you construct to represent each of your studies indicate which features you consider most important to the success of the study as a whole.

As we have indicated above, the features of the scientific study listed are the bold outlines or the skeletons of the structure. There is an elusive component that is difficult to articulate. It ties these components together and provides the soul of the study. It is this aspect that the professional scientists pursues while subconsciously engrossed in and executing all the others. For him the elements of the method we have listed are so familiar as to be undeserving of conscious consideration, like breathing, but just as necessary. It is in this spirit that P.W. Bridgeman made his remarks about the scientific method reproduced in appendix 1.

Questions

Review Bridgeman's statement on the scientific method.

(a) What do you suppose Bridgeman means when he writes, "In short, science is what scientists do, and there are as many scientific methods as there are individual scientists."

(b) What do you suppose Bridgeman means when he writes that scientists feel complete freedom to use any method or device whatever which might yield the correct answer?

(c) What procedure does a scientist follow in trying to guess a hypothesis? Is there any method one can follow in order to guess the solution?

C. SCIENTIFIC TRUTH

One fact about modern science is that it never deals with the question of "why" things are the way they are or of "why" things behave the way they do. The domain of scientific endeavor is to describe as simply as possible how things behave with one another in such a way that it enables them to predict the outcome of future events. If pushed by a layman with the question "Yes, yes I now understand 'how', but tell me 'why'?" The scientist is apt to answer "Because thats the way God made it." The layman may at first be disappointed with this reply, but only because he has not considered carefully what he means by "why". This question is a request to have something explained in terms of something more basic, i.e., that logical connections be made between some other basic truths or starting points. Scientific truth begins with descriptions of general time honored patterns of the behavior of nature.

Thus, basic scientific theory such as the theory of gravity is true if it is a good (i.e., useful) description of the behavior of that phenomenon. Search any text on physics for the section on gravitational theory, for example, and it will begin with a mathematical description of the attraction between two masses. There is no explanation of "why" they attract; that description is the point of entry into the theory. Hence, a theory is a model of reality whose usefulness has been substantiated by exhaustive experimental evidence.

Some models are "truer" than others for there is no unique way of representing the behavior of nature. Often several distinct models will do just as well at explaining a given set of experimental data. One chooses between them by examining larger sets of data until one is able to discard those that are proven inappropriate on the basis of new information.

Questions

(a) Is astrology a science?

(b) How do men choose between two scientific theories which describe the same phenomenon? In other words, what makes a theory good or bad?

(c) What do people mean when they say science is "exact"? Is what a scientist does when he guesses at answers to problems exact?

(d) Are there any experiences which you have had that you feel science could not help to explain? What are limitations to how far science can help us to understand the world?

(e) Construct argument based on experimental proof (or the lack of it) of the existence of ghosts and of extra-sensory-perception (E.S.P.).

D. THE PERSONAL MOTIVATIONS OF SCIENTISTS

A typical stereotype of the average scientist is that he is an unfeeling, (at worst) weird, (at best) genius, which by and large is a result of a general unfamiliarity with the scientist. We may rectify this by taking a close look at some of the personal reflections of a scientist. Appendix 2 contains selected quotes from an article by the gifted Nobel prize winning scientist R. P. Feynman on his feelings about science.

Questions

(a) What do you suppose motivates a scientist to work in his field? Compare this with your motives for choosing your major field.

(b) Have you ever felt similar to what Feynman is attempting to express?

(c) Think of a famous musician getting carried away with his music. Do you think a scientist can feel the same way about creating beautiful music?

(d) What does a religious man experience when he feels the nearness of God? Could this be the kind of feeling Feynman is trying to express?

(e) If science is a process of thinking and a feeling, why do you suppose the average man thinks scientists are cold and unfeeling? Isn't he motivated in a similar fashion to others? What is there that is usually creates this stereotype?

E. EXTENSIONS

An obvious alternative to classroom discussions or homework assignments in which the entire class participates is a good selection of reading material on the philosophy and history of science. There are many books discussing the history of science which are elementary enough to be of use at this time. There are some good introductory books on the philosophy of science which might be recommended. Perhaps, some students would find the biographies of various scientists interesting. It is suggested that each instructor prepare a bibliography of appropriate books available in his school's library.

As a beginning we would recommend "The Sleepwalker" by A Koestler.

It contains an exciting account of the process of discovery as well as the discoveries of the great astronomers. Below are selected parts of the preface of the book which describe Koestler's approach.

> "It is a personal and speculative account of a controversial subject. It opens with the Babylonians and ends with Newton, because we still live in an essentially Newtonian universe."

> "Secondly, I have been interested, for a long time, in the psychological process of discovery as the most concise manifestation of man's creative faculty - and in that converse process that blinds him towards truths which, once perceived by a seer, become so heartbreakingly obvious."

> "The progress of Science is generally regarded as a kind of clean, rational advance along a straight ascending line; in fact, it has followed a zig-zag course, at times almost more bewildering than the evolution of political thought. The history of cosmic theories, in particular, may without exaggeration be called a history of collective obsessions and controlled schizophrenias; and the manner in which some of the most important individual discoveries were arrived at reminds one more of a sleepwalker's performance than an electronic brain's."

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APPENDIX 1

The following is exerpted from an article by Percy Bridgeman, page 1 of Reader 1 of the Harvard Project Physics Series.

On Scientific Method by Percy W. Bridgeman

It seems to me that there is a good deal of ballyhoo about scientific method. I venture to think that the people who talk most about it are the people who do least about it. Scientific method is what working scientists do, not what other people or even they themselves may say about it. No working scientist, when he plans an experiment in the laboratory, asks himself whether he is being properly scientific, nor is he interested in whatever method he may be using as method. When the scientist ventures to criticize the work of his fellow scientist, as is not uncommon, he does not base his criticism on such glittering generalities as failure to follow the "scientific method", but his criticism is specific, based on some feature characteristic of the particular situation. The working scientist is always too much concerned with getting down to brass tacks to be willing to spend his time on generalities.

Scientific method is something talked about by people standing on the outside and wondering how the scientist manages to do it. These people have been able to uncover various generalities applicable to at least most of what the scientist does, but it seems to me that these generalities are not very profound and could have been anticipated by anyone who knew enough about scientists to know what is their primary objective. I think that the objectives of all scientists have this in common - that they are all trying to get the correct answer to the particular problem in hand. This may be expressed in more pretentious language as the pursuit of truth. Now if the answer to the problem is correct there must be some way of knowing and proving that it is correct - the very meaning of truth implies the possibility of checking or verification. Hence, the necessity for checking his results always inheres in what the scientist does. Furthermore, this checking must be exhaustive, for the truth of a general proposition may be disproved by a single exceptional case. A long experience has shown the scientist that various things are inimical to getting the correct answer. He has found that it is not sufficient to trust the word of his neighbor, but that if he wants to be sure, he must be able to check a result for himself. Hence, the scientist is the enemy of all authoritarianism. Furthermore, he finds that he often makes mistakes himself and he must learn how to guard against them. He cannot permit himself any preconception as to what sort of results he will get, nor must he allow himself to be influenced by wishful thinking or any personal bias. All these things together give the "objectivity" to science which is often thought to be the essence of the scientific method.

But to the working scientist himself all this appears obvious and trite. What appears to him as the essence of the situation is that he is not consciously following any prescribed course of action, but feels complete freedom to utilize any method or device whatever which in the particular situation before him seems likely to yield the correct answer. In his attack on his specific problem he suffers no inhibitions of precedent or authority, but is completely free to adopt any course that his ingenuity is capable of suggesting to him. No one standing on the outside can predict what the individual scientist will do or what method he will follow. In short, science is what scientists do, and there are as many scientific methods as there are individual scientists.

APPENDIX 2

The following paragraphs are quotations from "The Value of Science" by Richard P. Feynman. The article is found in Harvard Project Physics, Reader 1.

"Another value of science is the fun called intellectual enjoyment which some people get from reading and learning and thinking about it, and which others get from working in it. This is a very real and important point and one which is not considered enough by those who tell us it is our social responsibility to reflect on the impact of science on society."

"I have thought about these things so many times alone that I hope you will excuse me if I remind you of some thoughts that I am sure you have all had - or this type of thought - which no one could ever have had in the past, because people then didn't have the information we have about the world today.

For instance, I stand at the seashore, alone and start to think. There are the rushing waves...mountains of molecules, each stupidly minding its own business...trillions apart...yet forming white surf in unison.

Never at rest...tortured by energy...wasted prodigiously by the sun... poured into space. A mite makes the sea roar.

Deep in the sea, all molecules repeat the patterns of another until complex new ones are formed. They make others like themselves...and a new dance starts.

Growing in size and complexity...living things, masses of atoms, DNA, protein...dancing a pattern ever more intricate.

Out of the cradle onto the dry land...here it is standing...atoms with consciousness...matter with curiosity.

Stands at the sea...wonders at wondering...I...a universe of atoms... an atom in the universe."

The same thrill, the same awe and mystery, come again and again when we look at any problem deeply enough. With more knowledge comes deeper, more wonderful mystery, luring one on to penetrate deeper still. Never concerned that the answer may prove disappointing, but with pleasure and confidence we turn over each new stone to find unimagined strangeness leading on to more wonderful questions and mysteries - certainly a grand adventure?

It is true that few unscientific people have this particular type of religious experience. Our poets do not write about it; our artists do not try to portray this remarkable thing. I don't know why. Is nobody inspired by our present picture of the universe? The value of science remains unsung by singers, so you are reduced to hearing - not a song or a poem, but an evening lecture about it. This is not yet a scientific age."

APPENDIX 3

The following account of Kepler's study of the "Cosmic Mystery" and his solution of the five perfect solids are parts of Chapter II of "The Sleepwalkers" by Arthur Koestler, published by Universal Library, Grosset & Dunlap:

> 'For physical, or if you prefer, for metaphysical reasons', he then began to wonder why there existed just six planets 'instead of twenty or a hundred', and why the distances and velocities of the planets were what they were. Thus started his quest for the laws of planetary motion.
>
> At first he tried whether one orbit might perchance be twice, three or four times as large as another. 'I lost much time on this task, on this play with numbers; but I could find no order either in the numerical proportions or in the deviations from such proportions." He warns the reader that the tale of his various futile efforts 'will anxiously rock thee hither and thither like the waves of the sea....'
>
> ...'I lost almost the whole of the summer with this heavy work. Finally I came close to the true facts on a quite unimportant occasion. I believe Divine Providence arranged matters in such a way that what I could not obtain with all my efforts was given to me through chance; I believe all the more that this is so as I have always prayed to God that he should make my plan succeed, if what Copernicus had said was the truth'....
>
> The occasion of this decisive event was the aforementioned lecture to his class, in which he had drawn, for quite different purposes, a geometrical figure on the blackboard. The figure showed (I must describe it in a simplified manner) a triangle fitted between two circles; in other words, the outer circle was circumscribed around the triangle, the inner circle inscribed into it....

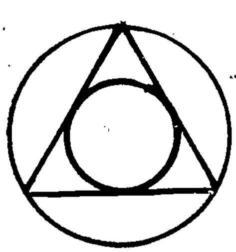

Fig. 18

As he looked at the two circles, it suddenly struck him that their ratios were the same as those of the orbits of Saturn and Jupiter, The rest of the inspiration came in a flash. Saturn and Jupiter are the 'first' (i.e. the two outermost) planets, and 'the triangle is the first figure in geometry. Immediately I tried to inscribe into the next interval between Jupiter and Mars a square, between Mars and Earth a pentagon, between Earth and Venus a hexagon....'

It did not work-not yet, but he felt that he was quite close to the secret. 'And now I pressed forward again. Why look for two-dimensional forms--and, behold dear reader, now you have my discovery in your hands!...'

The point is this. One can construct any number of regular polygons in a two-dimensional plane; but one can only construct a limited number of regular solids in three-dimensional space. These 'perfect solids', of which all faces are identical, are: (1) the tetrahedron (pyramid) bounded by four equilateral triangles; (2) the cube; (3) the octahedron (eight equilateral triangles); (4) the dodecahedron (twelve pentagons) and (5) the icosahedron (twenty equilateral triangles)....

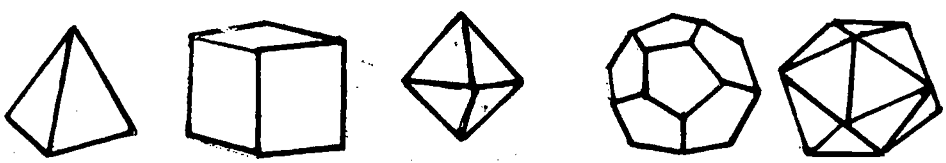

Fig. 19

They were also called the 'Pythagorean' or 'Platonic' solids. Being perfectly symmetrical, each can be in *inscribed* into a sphere, so that all of its vertices (corners) lie on the surface of the sphere. Similarly each can be *circumscribed* around a sphere, so that the sphere touches every face in its centre. It is a curious fact, inherent in the nature of three-dimensional space, that (as Euclid proved) the number of regular solids is limited to these five forms. Whatever shape you choose as a face, no other perfectly symmetrical solid can be constructed except these five. Other combinations just cannot be fitted together....

So there existed only five perfect solids - and five intervals between the planets! It was impossible to believe that this should be by chance, and not by divine arrangement. It provided the complete answer to the question why there were just six planets 'and not twenty or a hundred'.....

'It is amazing!' Kepler informs his readers, 'although I had as yet no clear idea of the order in which the perfect solids had to be arranged, I nevertheless succeeded...in arranging them so happily, that later on, when I checked the matter over, I had nothing to alter. Now I no longer regretted the lost time; I no longer tired of my work; I shied from no computation, however difficult. Day and night I spent with calculations to see whether the proposition that I had formulated tallied with the Copernican orbits or whether my joy would be carried away by the winds.... Within a few days everything fell into its place. I saw one symmetrical solid after the other fit in so precisely between the appropriate orbits, that if a peasant were to ask you on what kind of hook the heavens are fastened so that they don't fall down, it will be easy for thee to answer him. Farewell!'

APPENDIX 4

Kepler's three laws concern the general properties of the motion of the planets in their orbits about the sun. Although these laws appear innocent and simple, Kepler spent twenty-two years of his life arriving at them and wrote two volumes describing the process of that discovery and the implications of the laws. The contribution of these laws to the development of classical physics was as important as the contribution of Einstein's famous law for mass energy conversion, viz. $E=mc^2$, was to the development of modern physics. Kepler's statement of the laws was more dramatic than our concise version given below, but our statement contains the essential features of these laws.

Kepler's Laws:

1. The path of a planet in its orbit about the sun is an ellipse and not a circle with the sun as one focii.
2. The motion of each planet may be characterized by noting that an imaginary line from the sun to the planet traces out equal areas in equal times.
3. The ratio of the period, T, of the nearly circular orbit of the planet is related to its average distance, R, from the sun by: T^2 is proportional to R^3.