THE PSYCHOLOGICAL BASES
OF
SCIENCE—A PROCESS APPROACH

AAAS Commission on Science Education

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INTRODUCTION

The experimental science sequence for elementary grades, Science--A Process Approach, prepared under the auspices of the AAAS Commission on Science Education, is based, as the title implies, on a process approach to science. The primary objective of each exercise throughout the sequence is to teach one or more of the processes of science. The materials in the first and second experimental editions were prepared in two 8-week writing sessions (1963 and 1964) by teams of approximately 40 scientists and teachers, working at Stanford University. Scientists and teachers prepared the materials of the third experimental edition in the summer of 1965 at Michigan State University, and the first revision of the third experimental edition at the University of Maryland in the summer of 1966. The revisions and additions are based on suggestions from teachers in fourteen tryout centers. In 1967 the Xerox Corporation was selected to publish Science--A Process Approach and to market the entire program to schools throughout the United States and its territories.

In preparation for the writing sessions of 1963 and 1964, a panel of scientists and teachers was appointed to prepare statements of the philosophical approach and suggested guides and outlines for the summer writers. This brochure consists of the two papers prepared for the two summer writing sessions and a statement on psychological issues of Science--A Process Approach written by Robert Gagné, Professor of Educational Psychology, University of California, Berkeley, for presentation at regional conferences of tryout teachers held during the school year 1964-65. The titles of the three papers are as follows:

1. "Psychological Issues in Science--A Process Approach" (for regional conferences)

2. "The Individual Basis of Scientific Inquiry" (for 1963 writing session)

3. "The Scientific Approach to Knowledge" (for 1964 writing session)

The paper prepared for the writing session of 1963, "The Scientific Approach to Knowledge," was written by Robert Gagné with the assistance of Mary Lela Sherburne and a panel consisting of Burton H. Colvin, Head, Mathematics Research Laboratory, Boeing Scientific Research Laboratories, Seattle, Chairman; Donald Barr, Headmaster, Dalton School; E. U. Condon, Department of Physics, Oberlin College and Washington University; Edward L. Haenisch, Head, Department of Chemistry, Wabash College; Johns W. Hopkins, Department of Biology, Washington University; Richard H. Jahns, School of Earth Sciences, Stanford University; Arthur H. Livermore, AAAS; John R. Mayor, AAAS; and John Sternig, Director of Educational Services, Field Enterprises Educational Corporation.

The paper for the writing session of 1964, "The Scientific Approach to Knowledge," was written by Robert Gagné with the assistance of the following panel: Wallace R. Brode, American Chemical Society; Burton H. Colvin; Raymond T. Ellickson, Department of Physics, University of Oregon;

Donald Ford, Educational Services Incorporated; Edwin B. Kurtz, Jr., AAAS and Department of Botany, University of Arizona; Arthur H. Livermore; John R. Mayor; Illa Podendorf, The Laboratory Schools, University of Chicago; Henry H. Walbesser, Jr., AAAS and the University of Maryland; and Robert T. Ward, Ford Foundation, University of the Philippines.

This publication is sponsored by the AAAS Commission on Science Education, of which Professor Paul B. Sears of Yale University was the first chairman. Dr. Leonard M. Rieser, Dartmouth College, has been chairman of the Commission beginning in 1966. It is prepared for the use of teams and individuals who will continue the revision of Science--A Process Approach, for teachers and consultants in the centers, and for other interested persons.

As one activity in fulfilling its responsibilities for the improvement of science education, and as a background paper for the preparation of Science--A Process Approach, the Commission sponsored the preparation of a statement of the purposes and objectives of science education in school. This statement, with a foreword by Dr. Paul Sears, is presented in the following pages as part of the Introduction to this monograph. The foreword and statement were published in the Journal of Research in Science Teaching, Volume 2, pages 3 through 6 (1964), and are reprinted here with the permission of Dr. Craig Sipe, editor of the Journal.

Statement of Purposes and Objectives of Science Education in School

Foreword by Paul B. Sears
Yale University, New Haven, Connecticut, and Chairman,
AAAS Commission on Science Education

Statement by William Kessen
Yale University, New Haven, Connecticut

Foreword

In 1848 a group of men associated themselves for the advancement of science. They felt the need of mutual encouragement, better facilities, and wider usefulness than were accorded scientists at the time. The following century and a quarter have seen the introduction of science into school curricula, a vast increase in scientific research and the recognition of science as an adjunct to statecraft as well as a handmaiden of economic activity.

The advancement of science poses different problems at different times. It must have depended upon tolerance during the Middle Ages, upon personal wealth and leisure during the Renaissance, and certainly up through Darwin's day. More recently it has required academic recognition and the provision of costly space and equipment. Today it needs, as never before, wide public understanding and support, for it is thus that the work of scientists is chiefly sustained.

That the applications of science are essential to human health and the modern economy, to say nothing of conveniences, is clear enough. Yet in the midst of these abundant gifts, there is danger that deeper values may be overlooked. One need not read very far back into history to appreciate what confidence in natural order has done to eliminate dark and evil superstition. Nor does anyone who has been fortunate enough to be introduced to first-hand experience with natural phenomena need to be convinced of the rich delight thus afforded to the seeing eye and understanding mind.

But the same enlightenment that has done away with crude fears imposes a new responsibility. In this, after all, is the most basic of all the many roles of science in the modern world, for it gives to man the power to foresee and judge the consequences of his own actions in relation to the natural world of which he is inseparably a part. The many privileges conferred by science and technology do not include license to act without regard to the rules of experience, nor do the deepest satisfactions from science consist of enjoying merely the conveniences that come from its applications. Rather they lie in the ability to understand and appreciate the magnificent universe that contains us.

These benefits can only come as the generality of mankind acquires convincing experience in the field of the sciences. Thus it is that the American Association for the Advancement of Science, now grown from its 461 charter members to some 90,000, with more than 300 affiliated societies and academies, has established a Commission on Science Education to foster, in every way possible, scientific literacy among the American people.

This commission believes that experience with science must begin with the learning of language and continue throughout the educational process. It seeks to go behind the present fruitful studies in course improvement, so largely devoted to each of the various sciences as separate entities, and to weld them into a harmonious whole that will be built into the educational birthright of each of us. To that end it has attempted to formulate a statement of its objectives for science education in the elementary school to serve as a guidepost along the way.

The Statement was prepared by Professor William Kessen, of the Department of Psychology and Child Study Center, Yale University, with the assistance of the Commission and a panel of consultants.

Statement

There is joy in the search for knowledge; there is excitement in seeing, however partially, into the workings of the physical and biological world; there is intellectual power to be gained in learning the scientist's approach to the solution of human problems. The first task and central purpose of science education is to awaken in the child, whether or not he will become a professional scientist, a sense of the joy, the excitement, and the intellectual power of science.

Education in science, like education in letters and the arts, will enlarge the child's appreciation of his world; it will also lead him to a better understanding of the range and limits of man's control over nature.

Science as Enquiry

Science is best taught as a procedure of enquiry. Just as reading is a fundamental instrument for exploring whatever may be written, so science is a fundamental instrument for exploring whatever may be tested by observation and experiment. Science is more than a body of facts, a collection of principles, and a set of machines for measurement; it is a structured and directed way of asking and answering questions. It is no mean pedagogical feat to teach a child the facts of science and technology; it is a pedagogical triumph to teach him these facts in their relation to the procedures of scientific enquiry. And the intellectual gain is far greater than the child's ability to conduct a chemical experiment or to discover some of the characteristics of static electricity. The procedures of scientific enquiry, learned not as a canon of rules but as ways of finding answers, can be applied without limit. The well-taught child will approach human behavior and social structure and the claims of authority with the same spirit of alert skepticism that he adopts toward scientific theories. It is here that the future citizen who will not become a scientist will learn that science is not memory or magic but rather a disciplined form of human curiosity.

The Scientific Attitude

The willingness to wait for a conclusive answer--the skepticism that requires intellectual restraint and the maintenance of doubt--is oftentimes difficult for adult and child alike. The discipline of scientific enquiry demands respect for the work of the past together with a willingness to question the claims of authority. The attitude of intelligent caution, the restraint of commitment, the belief that difficult problems are always susceptible to scientific analysis, and the courage to maintain doubt will be learned best by the child who is given an honest opportunity to try his hand at scientific enquiry. With his successes will come an optimistic appreciation of the strength of enquiry; with his failures will come an understanding of the variety and challenge of our ignorance. For the scientist, child and adult, novelty is permanent; scientific enquiry continually builds novelty into a coherent design, full of promise, always tentative, that tames our terror and satisfies for a while the human desire for simplicity.

The Procedures of Science

Scientific problems arise in the play of children just as they arise in the guided exploration of scientists. Astonishment in the presence of natural beauty, surprise--even frustration--at the failure of a prediction, and the demand for sense in the face of confusion are the beginnings of scientific enquiry. But how do we then proceed?

Among the most demanding of scientific tasks and certainly among the most difficult to teach is the statement of a problem. Is there a meaningful question to be asked? What techniques should be used to answer it? How does one go about making a prediction or developing a hypothesis? As he asks these questions, the student begins to learn how active enquiry can lead to testable questions and eventually to the solution of problems. He is introduced also to the pleasures and problems of inventive thought--of considering what might be as well as what is.

There are many ways to answer a provocative question in science and the child should come to recognize that he must adapt his method to the problem in hand. As he runs against different problems, the child will learn to use several sources of reliable information--observation, experiment, books, museums, and informed adults.

Whatever the problem, the child's ability to observe should be extended so that he understands the wide range of observations possible even when simple phenomena are under study. He must learn to order the evidence of all his senses.

Attention to the complex activity of comparison of phenomena will introduce the child to an essential task in science--the perception of differences and similarities among events.

The child will use his ability to observe and to compare in building systems of classification and in recognizing their usefulness and their limitations in science.

The child should learn to use the instruments of science. As he studies these instruments, the teacher is given an opportunity to instruct the child in measurement. He will learn the need for precision in measurement, the importance of agreement among observers, and the relations among different systems of measurement.

The use of laboratory techniques--especially the experiment--deserves special attention. The experiment is the sharpest tool of science and in devising an experiment, the child exercises his ability to pose a question, to consider possible answers, to select appropriate instruments, to make careful measurements, and to be aware of sources of error. It is unlikely that children in the first years of school will manage well all aspects of sound laboratory procedure but the best lessons of the experiment can be taught only to the child who is actively engaged with the equipment and procedures of the laboratory. The teacher must adapt his desire for precision to the child's excitement in the search; a premature demand for exactness in experimental manipulation may blunt the student's commitment and pleasure.

After the problem is posed, a hypothesis developed, and the data gathered, the science student must evaluate evidence and draw conclusions. Sometimes this is a simple step; sometimes it involves the review and modification of the entire plan with renewed attention to problem, to hypothesis, and to data-protocols. The goal is to make sense of the data and the pursuit of this goal will on occasion lead to the detection of an error or to the design of another study. It may also lead to the invention of a model or theory through which we can comprehend data.

Throughout the course of science education, the need to communicate is present. Describing a bird to his class, graphing a mathematical function, writing an experimental paper--experience with each mode of report is essential to the development of the science student.

The child's ability to communicate in science will both depend upon and contribute to the achievement of this most general goal of the curriculum--accurate and effective communication.

The procedures of science described here in the context of early science education are recognizably the procedures of science at all levels of sophistication. Scientific enquiry is a seamless fabric. The content will change, the demand for precision will vary, the generality of conclusion will be different, the interrelation of studies will be understood in different ways, but the procedures and attitudes of scientific study remain remarkably the same from the time the kindergarten child wonders about color to the time the graduate physicist wonders about particle emission.

Scientific Knowledge

The facts and principles of science change with each advance in our understanding of the world. For this reason, it is difficult to forecast with precision what scientific content the child should know. Nonetheless, it is possible to sketch in outline the scientific knowledge that the properly educated child will possess within the first ten years of school. A knowledge of the basic findings of centuries of scientific enquiry gives boundaries and direction to the child's active exploration of his world. Under the governing premise that the curriculum in science must be defined by the child's growing comprehension of nature's order and beauty more than by the conventional categories of scientific knowledge, the child should know as much as he can actively seize about the universe, its galaxies, our solar system, the earth, and his immediate environment; the range of measurements used to describe astronomical and geological phenomena; the structure and reactions of matter from the smallest particles to their combination in minerals and rocks; elements, compounds and mixtures, large and small molecules, atoms, protons, neutrons, and electrons; the conservation and transformation of energy; the electromagnetic spectrum, energy of motion and potential energy, electrical energy and chemical energy; force and work, gravitational and magnetic fields; the interaction between living things and their environment; animal and human behavior, the relation between biological structure and function, reproduction, development, genetics, evolution, and the biological units--cell, organism, and population.

Science cannot be divided easily into labeled categories without loss. An emphasis on scientific principles that bridge the conventional subject-matter divisions will improve and simplify the teaching of science, making it more easily understood and more productive of meaningful problems for the child's own enquiry.

Scientific enquiry, moreover, is partner and peer of the traditional divisions of study; decisions about education in science must always be made with consideration of the relation of science to the child's other studies. Levers and poems, energy exchange and historical analysis, genetics and geography-- all present to the child an opportunity to extend his reach into the world and, in their different ways, all present to the child an opportunity to see beauty.

The Child and the Teacher

Rising above any statement of objectives for education is an irreducible fact. Teaching is an exchange between people. This simple human fact is both problem and promise for education in science as it is for all education. The child can understand only what he has been prepared to understand, the teacher can teach only what he knows, and the meeting of the prepared child with skillful teacher is an unforgettable encounter for them both. In the successful educational encounter, the child will become an active searcher for knowledge and the teacher will form attitudes toward enquiry as well as offer information about the world. The related and intricate problems of teacher training and the nature of learning are closely intertwined with the goals of science education. Science, rooted in man's curiosity and love of order, is called to its full humanity by the child's desire to know.

PSYCHOLOGICAL ISSUES IN

SCIENCE--A PROCESS APPROACH

Robert M. Gagné
University of California, Berkeley

A lecture delivered to regional conferences of tryout teachers in Washington, D. C., 1964, and in San Francisco and Chicago, 1965.

I think that all of you who are working with the exercises of Science--A Process Approach realize that you are engaged in a great experiment. Furthermore, it is an experiment which itself attempts to follow and to use the methods of science. Particularly, this experiment is one which is quite explicit about its goals. The hypotheses that are being tested are based upon a straightforward logic, and they are open to examination by any intelligent person, whether scientist, teacher, parent, or even student. As with all scientific hypotheses, they may be incomplete, or they may even turn out to be entirely incorrect--nevertheless, it would be a rare person indeed who would not agree that they are well worthy of the effort of testing. What we are all engaged in is the enterprise of finding out just how well these hypotheses work out.

What are these hypotheses, and what is their derivation? This is what I should like to describe to you, as well as I can. They have not been adventitiously derived. Instead, they represent a serious and systematic view of how scientific capabilities may be developed within the human individual, of how he can become an adult who is attuned to the complexities of knowledge which represent our "scientific" way of understanding the modern world.

Objectives

We begin with an idea of what we want to accomplish--what is it we want the individual to be able to do--how is it we want him to function in today's world. Most scholars and commissions of scholars who have studied the question of educational goals have emphasized three purposes:

1. vocational--the individual should be able to pursue a satisfying life work;
2. citizenship--the individual should be able to exercise responsible citizenship in his relations with other people in his community, state, and nation; and
3. self-fulfillment--the individual should be able to obtain and share with others esthetic satisfaction.

Science education has all of these goals, and none should be neglected. Of course, we are interested in establishing the conditions of education which will make it possible, for those who are capable, to become creative and productive scientists--the vocational goal. Science education is also legitimately concerned with responsible citizenship--we are interested in developing a citizen who understands the ways of science and scientists, the costs of science, the societal benefits of science, the determination of public policy about science. In other words, we want him to possess what some have called scientific literacy--to be able to read about science in newspapers or elsewhere, and to make responsible judgments about what he reads or hears. And by no means least, we should like our student to appreciate science, to experience personally the satisfaction of scientific discovery, the compelling experience of inference from systematically organized facts, the intellectual finality of deduction from a general principle to a specific instance. We want him to know from these experiences that "beauty" in science is not just a metaphor, but an attainable intellectual experience.

Alternative Approaches

There surely must be a great deal of agreement on these goals of scientific education. But when one gets to the practical matter of how to achieve them, there are disagreements. When you bring together a group of physicists, biologists, chemists, earth scientists, and mathematicians to try to agree on what science education should be, the disagreements can get pretty lively. And when you add to this the startling idea that one might try to begin designing such education with the earliest grades of school--one reaches a condition which approaches pandemonium at times. There is of course something to be said for beginning at the highest level and working downwards. There are also advantages to working the other way. At any rate, as you know, the latter is what we tried to do, and we did have the periods of pandemonium.

In order to begin at the earliest level, one must have a rationale which connects adult behavior with child behavior, and this is the point at which some of the disagreements arise. Let me summarize in brief form some of the points of view which seem to have been encountered:

1. The "content" view. This view is that the best way to learn science is to start to study physics, or biology, or chemistry, in the earliest grades. Not "how a seesaw works," but the relationship between force and energy. Not "how to feed a rabbit," but the process of metabolism. Naturally, one can't teach these scientific ideas all at once, or perhaps very rapidly in the early grades, but one can nevertheless painstakingly build up an understanding of them beginning with very simple notions and progressing gradually from these. This view has some definite merits, and no one would want to say that it is wholly infeasible. For one thing, it correctly identifies the deficiency in much elementary science teaching as being composed of isolated facts which perhaps never do get connected with a larger body of knowledge. And it is surely correct in its premise that the children are not too young to learn about science systematically, just so long as what is presented is understandable to them in terms of their previous knowledge. What is wrong with this view, then? Simply that it seems likely to run into the difficulty that the background knowledge required by the child would require a great deal of time and effort to provide. One can't get very far with force and energy without teaching the child how to make systematic observations, inferences,

and measurements. And if one proposes to do this, the question then arises as to whether one should try to teach observation, inference, and measurement in relation to force and energy alone, or whether one ought to try to teach them with reference to animal digestion, solutions of chemicals, and so on. Having arrived at this point in thinking, one is led back to a "process" point of view after all.

2. The "creativity" view. A very different point of view is that since scientists are creative individuals, one should undertake deliberately to "train creativity." In its extreme form, this view is that there exists a general trait in each individual which is subject to improvement through training, and which will when so developed increase the tendency of the individual to be creative in a variety of fields, including science. The kind of training needed to accomplish this, presumably, is a series of situations in which the individual practices having novel ideas and being rewarded for having them.

This point of view has some grains of truth in it, if these are properly stated. There is certainly evidence that children or adults who are rewarded for having novel ideas do tend to produce more of them (Taylor, 1964; Covington and Crutchfield, 1965). One of the neatest experimental studies of this effect that I know of showed clearly that training which encouraged children to formulate new questions, restate the problem in their own words, and generate ideas created a generalized tendency for children to do this even when they were presented with entirely new and different problems (Crutchfield and Covington, 1963). One of the most interesting findings of this study, in fact, was that this result could be obtained with training that lasted only a few hours. In a way this is disturbing to those who favor this "creativity" point of view. It is almost too easy. It doesn't really look like a general trait, but like "sensitization," as the authors of this study pointed out. Perhaps anyone can be "creative," if he is given the proper "sensitization."

Now, I do not wish to overemphasize this particular finding; more research along these lines needs to be done. What I do wish to emphasize is this: No one would think of denying that under the proper conditions, people can be "creative," and under other conditions, they cannot be. But to jump from such a fact to the idea of a generalizable trait of "creativity" which can be trained is quite unjustified. There is no current evidence which shows that one can legitimately speak of a general trait of "creativity" that is independent of other human abilities. And in making this fearful logical leap, those who speculate about it are ignoring some most important lessons of psychological research accumulated over the years. We all know that it has not yet been possible to demonstrate a single unitary trait of general intelligence, and many doubt that it ever will be. We know that many traits which were thought to be unitary have definitely turned out not to be--honesty, introversion, conservatism, flexibility, dominance, and many others too numerous to mention. As for the effects of training, these too have tended to show themselves as rather specific changes, on the whole.

3. The "process" approach. This approach seeks a middle ground between the extremes I have mentioned. At the same time, it attempts to capitalize upon the best features of both these other approaches. Specifically, it rejects the "content approach" idea of learning highly specific facts or principles of any particular science or set of sciences. It substitutes the notion of having children learn generalizable process skills which are behaviorally specific, but which carry the promise of broad transferability across many subject matters. The process approach also rejects the notion of a highly generalizable "creative ability" as a unitary trait. Instead, it adopts the idea that novel thought can be encouraged in relation to each of the processes of science--observation, inference, communication, measurement, and so on. The point of view is that if transferable intellectual processes are to be developed in the child for application to continued learning in sciences, these intellectual skills must be separately identified, and learned, and otherwise nurtured in a highly systematic manner. It is not enough to be creative "in general"--one must learn to carry out critical and disciplined thinking in connection with each of the processes of science. One must learn to be thoughtful and inventive about observing, and about predicting, and about manipulating space and time, as well as about generating novel hypotheses.

Key Ideas of the Process Approach

And so we come to the process approach itself. Its basic premises may be stated as follows:

1. The scientists' behaviors in pursuing science constitute a highly complex set of intellectual activities which are, however, analyzable into simpler activities.

2. These intellectual activities (processes) are, as most scientists would agree, highly generalizable across scientific disciplines. It is not difficult for a physicist to become a biochemist, or vice versa, so long as language and techniques are learned. It is not even difficult for a meteorologist to become a psychologist--predicting the weather and human behavior may have comparable degrees of uncertainty.

3. These intellectual activities of scientists may be learned, and it is reasonable to begin with the simplest ones and build the more complex activities out of them, since this seems to be in fact the way they are organized.

4. Accordingly, one can construct a reasonable sequence of instruction which aims to have children acquire process skills, beginning with simple kinds of observation, and building progressively through classifying, measuring, communicating, quantifying, organizing through space and time, to the making of inferences and prediction. As further building occurs, one finds it possible for students to learn how to make operational definitions, how to formulate testable hypotheses, how to carry out experiments, and how to interpret data from experiments. At this point, probably, one may well have a pretty sophisticated student on his hands.

5. At the end of such instruction, the student will not necessarily know anything which can be identified as physics, or chemistry, or biology, or geology. What will he know, then? Perhaps something like this: A scientist should be able to tell this student what he (the scientist) is studying, and the techniques he is using, and what he has found, in a relatively brief fashion, and have the student display a rather profound understanding of it immediately. Presumably, such a student will not have to take a course in the philosophy of science in order to display this understanding.

What does this mean the student is ready for in terms of additional science instruction? I do not feel very certain of this answer. My guess is something like this: Such a student should be able to learn any given science, in terms of its theoretical structure, in about half the time that it would otherwise require. (If this means shorter courses in specific sciences, I'm all for that.)

Obviously, one of the key ideas of the process approach is the progressive building of more complex intellectual processes from simpler ones. This is in fact one of the more fascinating central hypotheses of the whole approach. I recommend that you carefully examine the hierarchy chart for the basic processes (published by the Xerox Corporation). The hierarchy chart illustrates this building process. The chart contains a separate hierarchy for each process except Communicating and Predicting, which are combined. Relationships among the process hierarchies are also shown. We do not know that the chart represents ideal progressions--in fact, we doubt that this is so. But the process hierarchies are sensible progressions, and this is probably the important thing.

Let me try to illustrate how these intellectual processes build upon one another by choosing examples from Science--A Process Approach.

I begin with an admirable exercise from Part Six, entitled Control of Variables 6, "Energy and Height."* In this exercise, children are learning to explore the meaning of the definition: "Energy is the ability to do work" by systematically plotting the relation of one physical variable to another. The variables they are relating in this case are the height of a cylinder on an inclined plane, and the distance it pushes a block when it rolls down the plane. Now if these students carry out this exercise with understanding (and I assume they will), they are really doing some pretty sophisticated science. How is it they are able to do this? How did they become so sophisticated?

The general answer is, their learning in this particular exercise has been preceded by a carefully planned set of exercises which have given them some prerequisite knowledges. And these in turn have been learned in a whole series of previous exercises contained in Science--A Process Approach. Let us see what the most important of these are.

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*Since this was written, this exercise has been revised and is now in Part Seven. It is called Experimenting 9, "Potential and Kinetic Energy." The comments on the original exercise, found on this page and the one following, still apply in large measure to the revised exercise.

First, they must be able to understand what is meant by "the property of being able to do work." Where has this come from? They are able to understand that in performing the operations they carry out, this is actually defining the concept of energy. In other words, they have the idea of the operational definition. In a most direct fashion, this has come from an immediately preceding exercise in which they have learned that work is force times distance. It has also come from other exercises, with different subject matter, but still providing instruction on operational definition.

But this is not the only precursor to the new knowledge. How do they know what is meant by a property of an object? By now this concept of an object property has been well established by means of a number of exercises which can readily be identified under the rubrics Communication, Classification, and Observation.

Another element of this exercise on energy, though, is that it involves the measurement of variables, and relating them by means of a graph. Do the students know how to make a graph, and interpret it? Yes, one can find a whole sequence of previous exercises in which this capability has been developed, not only through the actual graphing of simpler phenomena, but also through a development of their understanding of number.

Will the students who have made five measurements relating height to distance pushed be able to generalize this relationship beyond the measures they actually obtain? Yes, they should be able to do this, since they have had experience in predicting events from data in other earlier exercises.

Are they able to say or otherwise to report what they have done in relating the height of the cylinder to its energy? They certainly should be able to do so, insofar as the preceding exercises on communication have been properly planned. Suppose one asked the question as follows: "A cylinder on an inclined plane is said to have a certain amount of energy. Tell me how to measure this energy." One expects students who have had previous experience in communication exercises to have little difficulty answering this question precisely, thoroughly, and comprehensibly. They should not be talking about "things," or "pushes," or "ups" and "downs." One expects them to be able to talk about cylinders and planes and forces and distances.

The substance of this account is, then, that by the time the students of Science--A Process Approach reach this exercise on systematic manipulation of variables involved in energy, they know a great deal about how to set about it. The fairly complex sequence of thought, problem solving, and action which seems to be demanded by this exercise is not terribly difficult for them to acquire. For this complex behavior has been carefully built--beginning way back in kindergarten and first grade, where they first started to learn to observe and to classify and measure and describe. In a systematic way, subsequent learning has been brought about so that their performance of scientific activities, with a wide variety of subject matter, has gotten increasingly complex, increasingly competent, increasingly sophisticated.

As I have mentioned previously, the sixth grader who has learned science processes in this manner should be capable of studying science in junior high school in a way in which he is not now capable. This raises the interesting question of what kind of science should he take in junior high? But there is still another difference in this "new young man" of science, which seems at least equally important. This pertains to his reading about science, which I believe he will wish to do to a greater extent than ever. Reading about science and scientists is important, because this is the general part of his scientific education--the part that will make him scientifically literate, and also a good citizen about science, even if he doesn't ever become a scientist.

Now there are some very good books about science which are written at the vocabulary level of the fifth and sixth grader. But, generally speaking, they have been written under the assumption that these students know very little of the processes of science. Consequently they are likely to go to great lengths to explain something in simple terms that the student of Science--A Process Approach already knows about. Can you imagine a book, say, about the dating of geological strata, or about the circulation of the blood, which assumes that the reader does not have to be told:

1. what an operational definition is;
2. how to design an experiment;
3. how to control and manipulate variables;
4. what a hypothesis is;
5. how to interpret data?

I suspect that such a book would be a kind of "junior-level" Scientific American. It seems likely to me that books which are simply written, and yet which do not talk down to our "new young people" are going to be badly needed. May I urge any of you who are interested to write this kind of book?

I am about at the end of what I want to say. The experiment in which we--and particularly you--are all engaged, has a worthy purpose. It represents an attempt to establish the specific competencies in students which will make it possible for them to solve problems, to make discoveries, and more generally to think critically about science from their very early years onward. I am sure most of us who have tried our hand at writing the exercises tend to keep constantly in mind the hope that these children will have science "in their bones." I believe the approach of these materials is an admirable one not only for these positive reasons, but also because it avoids the extremes which represent the "too easy" roads to success which are (1) "teach atomic theory in the first grade," on the one hand, and (2) "develop the trait of creativity," on the other. The approach is based upon the idea that the best route to understanding and appreciation of science is by a careful and systematic building of increasingly complex human performances which include and make possible both flexible and disciplined thinking. Hopefully, this is the sort of competence which can lead, at a minimum, to a proper appreciation of science as a citizen, and at the other extreme, to the most highly original and inventive inspirations of science of which the human mind is capable.

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THE INDIVIDUAL BASIS OF SCIENTIFIC INQUIRY

A working paper prepared for the 1963 summer writing conference, Stanford University.

Two considerations must enter into planning for the early study of science: the nature of the child in his early years; and, the long-range view toward the child's acquisition of advanced skills and maturity. The child in the first four years of schooling can in no sense be characterized at any point as a finished product in any skill or understanding. He is in every sense "becoming," and definite steps should be taken to encourage his development. In the long-term consideration, he should gain the understandings and skills needed for the acquisition of higher levels of knowledge, for the eventual practice of science, and even for appreciation and understanding of science in a science-oriented society. Experience, skill, and knowledge, carrying the quality of generalizability to many areas of science, should be sought.

A Framework of Goals and Content in Terms of Processes

The Process Approach

In this paper early science instruction is approached in terms of the processes of science. In this approach the achievements of students in the early grades would be measured primarily in terms of their conquest of specific steps in building basic knowledges.*

There are recognized elements of commonness to scientific endeavor, basic skills and operations which are applied to the study of phenomena, and which are not so delimiting as to interfere with a broad definition of science and the practice of it. Further, there is some value, for purposes of curriculum building, in stating as clearly as possible these basic skills and operations. Thus, observing; describing; classifying; measuring; recognizing and using space, time, and number relationships; drawing inferences; experimenting and speculating; and developing a sense

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*How these "knowledges," fundamental to understanding and engaging in the processes of science, would be termed was the subject of various discussions during the preparation of this paper. In one sense, as these knowledges are referred to in the stated purpose of the materials to be prepared, they are "skills" or "competencies" which enable one to use knowledge effectively. Yet they must be regarded as far more than mere technical proficiencies. In an attempt to insure that words do not reduce the teaching of science into mere methods and skills, the term "knowledges" is used to imply skill, competence, ability, and the concomitant understandings.

of the limitation of these skills, are listed as some goals of learning. These skills are not ends in themselves, but a necessary means to the practice and understanding of science.

It is recognized, in framing the goals in terms of basic knowledges, that universality cannot be achieved. Certainly no one can satisfactorily define all the dimensions of anything so varied as the enterprise of science, or describe all the abilities, skills, and related understandings which might be utilized in pursuing it. Yet lack of universality is not to be considered as a basis for rejection of a thorough effort to teach as many of the knowledges as possible.

The Content Approach

The most commonly accepted approach to elementary science teaching is based upon content concepts and principles. In this subject-matter point of view, what is to be learned is expressed as a body of knowledge, descriptive relationships about the material world, and generalizations that provide the most widely applicable explanations of phenomena. While this approach has intuitive, emotional, and some logical appeal, it also has inherent difficulties and hazards of application in curriculum building. Organizing fundamental science concepts is an exercise of great complexity with as many points of view as there are organizers. Also, the rapid pace at which scientific knowledge changes and reorients its formulations of knowledge renders any formulation quickly out of date.

Framing the goals purely in terms of content may mean that the facts about the world, as science sees it, and the concepts and principles to be sought become ends in themselves. The nature of science as a dynamic, ongoing, open-ended process of investigating natural phenomena may readily be lost. Within a framework of content alone, it is also easier for the inexperienced teacher to be satisfied with teaching science by reading about it, telling, describing, and demonstrating. Measuring the achievement of students in purely verbal terms may thus be encouraged.

The Scientific Method and the Problem-Solving Approach

Another common way of organizing science in the elementary school, more widely used in the past, but found even now in some curricula, often is referred to as the scientific method approach. In this approach the steps in scientific reasoning and investigation are regarded as a fairly rigid, definite series. In more recent curricula, a looser interpretation of how to solve a problem may be applied, but often science is viewed as essentially a problem-solving technique that is learned largely through practice of the technique itself. Such an approach assumes that one learns science through repetition of certain definite sequences.

For example, one might begin with a growing plant, and proceed intensively from simple description of the events of growth, to the relationship of growth to other factors which can be varied, such as light and water, and end with inferences about the factors affecting growth. This method sounds like teaching of "processes." It has intuitive appeal because some "process skills" of science are indeed practiced in experience with particular content.

This approach, while feasible and often productive of results that appear to be satisfying, has some serious deficiencies. Such instruction tends to be narrow; it fails to establish a broad base of knowledge which can be generalized to any and all situations that the student may meet, either in dealing with the world or with advanced topics of instruction. Units of instruction which are designed in this "vertical" manner certainly can be made to lead the child to make new and exciting discoveries that may appear marvelous to the student, teacher, and observer. But the question is not whether a second-grader, for example, can be guided along a narrow path of practice in observation, inference, and experimentation in a plant project. Of course he can. Rather, it is one of priority and relevance in the light of this stage in a child's conceptual development. When he finishes the project, will his learning be the kind with the most mileage, the kind that will reach into the future and into many novel situations? Does this problem-solving approach provide the kind of learning with a high degree of generalizability that will extend into all areas of the child's life?

What evidence there is strongly suggests that this approach does not; that instead it tends to result in retention of specific content facts and perhaps also a set way of obtaining them. Further it may impose a logical structure, which the child can copy, but which is not necessarily interiorized. The child who is guided on a narrow straight-line path to scientific inquiry does not have the opportunity to build the multiple and differentiated operational performances, whose gradual elaboration will enable successful generalization and the relating of newly learned knowledges to novel problems he will encounter later.

The Implications of Studies of Learning

The implications of modern psychological studies of learning and transfer of training are clearly to the effect that high degrees of transfer or generalizability are not produced by practice on a narrowly defined task, nor on a series of such tasks, regardless of how intensive such practices may be. Recent studies in conceptual development in children also bear out the thesis that the growth of scientific concepts and logical thinking are related to a great deal more than mere practice of procedures.

In connection with these problems it is of interest to ask: What are some of the conditions of learning which can be introduced into the classroom to maximize the learning of processes and, one hopes, consequent generalizability of knowledges?

Two main conditions of the learning situation appear to be needed to attain such an objective:

1. Practice of the performance relevant to each newly acquired knowledge should involve the use of a wide variety of materials, in a wide variety of situations. An implication of this for developing units of instruction is that the achievement by the individual of a specific goal, understanding, or capability should be measured in terms of various kinds of performances (not merely verbal responses) and with various kinds of content.

2. The arrangement of the learning situation should be such as to insure that the overt activities required are produced from the individual's own internal processes, rather than being tied to specific stimuli provided by the teacher. In other words, learning will be most effective when relationships are "discovered" rather than "copied," when generalizations are attained rather than being imposed.

A reasonable interpretation of these various lines of thought leads to the idea that there are basic types of broadly applicable knowledges that underlie the practice and the understanding of science. They are the kinds of activities that every scientist engages in, yet does not stop to think about because he knows them so well. He observes; he makes accurate and reliable descriptions; he classifies; he measures; he perceives relationships in space and time; he draws reasonable inferences; he experiments. These are the skills that are generalizable to all kinds of science content. The problem of designing an elementary curriculum for the early grades is one of insuring that these kinds of skills are well-learned, so that they will form a firm basis for the later mastery of science as a disciplines.

The Basic Knowledges

The basic knowledges are those that are necessary for an individual to possess at as early an age as possible, in order to pursue seriously the study of science in the later elementary and junior high school. They are regarded as goals that will be the product of the kind and organization of instruction and units of teaching, as well as the maturation of the child.* They can be characterized in the following manner:

First, each of the basic knowledges consist of many subordinate skills and components proceeding from the simplest to those of considerable complexity.

Second, each subordinate knowledge is conceived of as building upon, and in a learning sense depending upon, all of the simpler subordinate knowledges in the sequence, as well as some in other sequences. A progression of sequences has been postulated which makes for a high probability of learning the next higher unit of basic knowledge, if the student has already mastered the related ones below; and for a low probability if he has not.

Third, these basic knowledges are thought of as something that the individual either possesses or does not possess. Accordingly, each is something the individual can learn, not merely a sequence he is exposed to. It is expected that materials can be written which express in specific terms the accomplishments desired for the student in response to certain units of instruction. These goals can be expressed in terms of activity words, such as classifying, measuring, recognizing, explaining, reading, identifying, demonstrating, computing, illustrating, constructing,

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*See definition of knowledges at bottom of page 9.

making, and others. Such words are to be preferred to terms which are more loosely defined, such as understanding and comprehending.

Fourth, a characteristic of these basic knowledges is that they can serve as a basis of units of instruction, either singly or in combinations of two or three. It needs to be borne in mind that what is sought in any case is a wide variety of experiences and content examples within which these various knowledges can be practiced.

The eventual goals of understanding are expressed in their broadest terms; that is, knowledge of the world as science sees it, of science as an enterprise, and of scientists. The sequence of units emphasizes that, while the curriculum is built in the framework of processes, it cannot be divorced from the body of content knowledge. In the early years, the knowledge of the world, as science sees it, is small. Some of the basic skills which can be developed at this age are really tangential to science. But as the child matures and advances in level, the basic knowledges converge more and more into the content and body of knowledge known as science. At the higher grades and advanced levels the processes and contents cannot be so profitably considered apart from one another.

Although not specifically described, it is thought that a sequence of mathematics should be included. As conceived, such a sequence has one unique and interesting characteristic: namely, that the particular knowledge units shown have been derived as requirements to support the other units in science. In other words, this mathematics is essential for science instruction.

A brief description and explanation of each of the sequences in the knowledge units follows. These are not definitive but suggestive. They are descriptions for teachers and curriculum makers, and accordingly are not expressed in terms the child is expected to use. For example, where one unit describes "drawing reasonable inferences from observation," it does not mean to say that the child should describe what he is doing, or be able to make a verbal response to a question so stated. It simply means that the child should be able to perform that particular relational action, perhaps using his own words (or even no words at all, if a suitable observation of his performance can be devised which excludes them).

Observing--Classifying

1. Observing likenesses and differences in single objects which vary in their physical characteristics as detectable by any of the senses (with emphasis on vision, hearing, and touch). Can the child learn to distinguish two cubes, identical to sight, but different in weight, or temperature? Ultimately, he should be able to identify differences (in whatever words) and likenesses in a wide variety of objects he has not previously seen; he will know what differences to look for.

2. Observing likenesses and differences among sets of objects in terms of the number (of objects) possessing common characteristics. Can the child learn to sort blocks of wood into categories such as red and green, and to tell how many there are, up to ten? Ultimately, he should

be able to divide a total set of unfamiliar objects into two or more subsets differing in some characteristic (exact name not important) and to tell how many objects are in each subset.

3. Observing and classifying in terms of the concepts larger-smaller, greater-lesser, higher-lower, nearer-farther, heavier-lighter. Can the child learn to arrange blocks into categories such that the first is larger than the second, the second smaller than the first, and so on? He should come to be able to do this for a variety of unfamiliar objects, including all the categories mentioned.

4. Ordering objects within categories which have been classified. Can the child proceed from the classification of larger-smaller to arrange a set of blocks in order with the largest first, the next largest second, and so on; or the heaviest first, the next heaviest second, etc.? He should learn to be able to do this for a variety of objects, whether or not he has seen them before, and for all the categories previously mentioned.

5. Correctly subdividing a set of unfamiliar objects into several categories of increasing inclusiveness. For example, can the child divide a set of blocks into the major category of rounded-angular; further subdivide these into 3-sided and 4-sided; and further subdivide these categories into rectangular-nonrectangular; and so on? The words used to describe the categories may be already familiar, or may be made so. The child should learn to do this task of classifying into smaller and smaller categories for a wide variety of objects.

6. Observing and classifying objects on the basis of "derived" characteristics requiring a kind of measurement, such as area and volume. A rectangle and a square may be shown to have the same area, if a paper model of one is cut and the cut pieces placed upon the other. The depths of equal volumes of water are different in a tall thin glass and a short one of large diameter. What is being learned is the equivalence and nonequivalence of objects in terms of properties which are not immediately observable, but must be derived from "operations." Ultimately, the child should learn to identify likenesses and differences in areas and volumes (in demonstrations of unfamiliar objects) by performing simple operations to determine the required identities (operations like pouring water from one container to another, cutting paper shapes to correspond, etc.).

7. Classifying likenesses and differences among rates of change (of state); understanding relative velocity and acceleration with reference to a wide variety of events. In a nonquantitative way, the child should learn to identify the relative velocities of a variety of events, like noise (fast), chemical reactions (some slow, some fast), growth (slower still), movements of physical objects. Following this, he can learn to classify speeds, like those which steadily increase (ball running down an inclined plane), those which go fast at first and then taper off (chemical reactions, growth), those which are cyclical (motion of a pendulum), and others. Ultimately, he should be able to classify and order a variety of different events, including some he witnesses for the first time.

8. Classifying and ordering relationships of physical events. The child should learn about many relationships, such as those between temperature and the solid-liquid-gaseous state; between pressure and temperature; between roughness of surface and the force of friction; between light and growth; oxygen and life, etc. Can he also learn to distinguish among degrees of such relationships; that is, the degree of effect apparent in these relationships, some of which are all-or-none, some of which are matters of other degree? Ultimately, he should be able to state (and order) several classes of relationships between a variety of different sets of events, even if they are shown to him for the first time.

9. Classifying events on the basis of inferred variables (e.g., energy, electric charge, etc.). The knowledge to be learned here is that of understanding certain inferred variables like potential energy. For example, can the child learn to be able to make the correct inference about the existence of potential energy from a number of different examples (inclined plane, object raised to a height, pendulum, etc.), and to distinguish these from others which are not potential energy? Can he do the same for the flow of electric current? The ultimate behavior desired is this: Upon being told the meaning of an unfamiliar inferred variable, and presented with several different examples, the student is able to distinguish those which are examples of the variable from those which are not.

Advanced level. Distinguishing the classes of events involved in "indirect" observation. What is seen and what is inferred in observing planets through a telescope, cells through a microscope, X-rays, Brownian movement, etc.?

Communicating in Science

1. Responding to and using, in oral communication, words for common objects. At the earliest level, the child must learn the meaning of words for objects. Presumably, there is still a good deal of this to be done at the kindergarten level. The child must learn what the names are for various classes of objects with which he comes in contact every day.

2. Oral communication with common words denoting relationships. The child has to learn the meaning of words, such as like-different; near-far; up-down; left-right; small-large (with two in the set); and others. He should learn to identify these relationship words accurately for a wide variety of objects and situations. When he meets an unfamiliar situation, he should be able to communicate these relationships accurately.

3. Oral communication of events; i.e., movement or change, and the categories of objects which enter into these events. For example, batteries are involved in turning on a flashlight, gasoline in making a car move, cold in making water turn to ice, and so on.

4. Responding to and using in oral communication class-names for larger categories such as plants, animals, food, furniture, shelter, and many others. After common objects can be named (see 1), the child needs to learn that these can be classified into more inclusive categories. He

should know, for example, that birds and dogs and cats are animals, but that the class animals includes other subcategories as well. (There are some fundamentals of logic involved here.) Ultimately, he should be able to communicate orally his understanding of these class relationships, for a group of unfamiliar objects.

5. Oral communication with comparative words. After mastering 2, the child is ready to learn about relationships such as higher-lower; greater-fewer; nearer-farther; larger-smaller; and others. Beginning with comparisons of two objects, he can progress to comparisons involving three or more. Can he say correctly that Block A is smaller than Block B, and that Block B is larger than Block A? Ultimately, he should be able to use these comparative words without error in a new situation.

6. Oral communication with general categories of scientific description: shape, size, distance, color, angles, etc. Now the child begins to describe things, using categories which represent objectively verifiable characteristics. Can he learn to describe an unfamiliar object in such a way that it could be reproduced--that is, in terms of its size, weight, color, shape, and so on? He should be learning how to do this accurately (not quantitatively, at this stage) for any unfamiliar object.

7. Describing in connected discourse and writing the characteristics of specific objects in verifiable language, and in terms of scientifically relevant categories. This is the most basic kind of scientific writing. Can the child learn to make adequate and comprehensive descriptions of unfamiliar objects?

8. Describing in connected discourse and writing the characteristics of unfamiliar events, in terms of time, velocity, force, acceleration, etc. When asked to observe events such as balls running down inclined planes, chemical reactions, plant growth, can the child learn to give an accurate description of the time, velocity, force, acceleration, and other dynamic characteristics? He should be able to do this comprehensively and accurately (although qualitatively) for a variety of different events.

9. Describing in connected discourse and writing a set of events contained in an unfamiliar demonstration involving one or more physical relationships. When shown a demonstration such as the evaporation and subsequent condensation of water, can the child learn to describe the relationships he observes (assuming he already is capable of describing objects and events, as in 7 and 8)? He should become capable of doing this well for a variety of demonstrations, not previously familiar to him.

10. Describing in connected discourse and writing the inferences to which one may be led by a demonstration, and distinguishing these clearly from the observed characteristics of objects, events, relationships. Having observed and described the observed facts about the evaporation and condensation of water, can the child learn to describe some basic inferences about this demonstration (such as particles and the density of media), and distinguish these clearly from the directly observable facts? This is a most important distinction, and deserves considerable emphasis.

11. Distinguishing and describing the activities of the observing scientist from those of the events observed. The idea of system, which should have been introduced in 9, is important here, as are the concepts of the observer and his point of view. What the child needs to learn particularly is to be able to distinguish clearly between the system of the scientist plus the phenomenon, and the system of the phenomenon itself; the differences introduced into the system by different points of view of the observer, etc. The exercises described by Karplus* are of particular relevance to this objective.

Advanced level. Describing the conditions of an experiment, in terms of what the experimenter does, the variables employed, the measures taken, etc., from a demonstration or from a brief statement of purpose. The "advanced" objective is, in simple terms, one of getting the student to the point of describing an experiment. Beginning with a statement like, "Describe an experiment to determine the effect of light on plant growth," he should be able to provide an adequate and comprehensive written description.

Measuring

1. Classifying likenesses and differences in objects on the basis of weight and distance dimensions. The basis of measurement is the establishment of identities in units of mass, time, and distance. As an initial introduction, the child needs to learn that objects may be classified as like or unlike in terms of these dimensions. Two blocks that have a difference in appearance may nevertheless be identical in weight; and vice versa. Ultimately, the child should be able to classify unfamiliar objects in terms of these characteristics.

2. Ordering objects along prescribed dimensions (mass and distance), and assigning numbers to these. Having learned to classify objects using these dimensions, the child needs to learn to order a variety of unfamiliar categories of objects along these dimensions. Can he learn to place a set of blocks of various three-dimensional shapes in order of the length of the longest base? Ultimately, he should be able to make such orderings, with assigned numerals, for a variety of unfamiliar objects.

3. Classifying sets of objects in terms of number categories, including those which are based on estimates. Initially, the child should learn to classify sets of different objects into categories which are identical in number (from 1 to 10). Proceeding from this point, he can also learn to make estimates of numerousness involving larger numbers. As an objective, he should be able to classify the numbers of sets of widely differing objects.

4. Using common instruments of measurement correctly. Based upon his previsouly acquired knowledge of "basic units," the child should learn to use such common instruments as balances, foot-rules, yardsticks,

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*Science Curriculum Improvement Study, University of California, Berkeley as well as clocks and other timing devices. The classifications he has previously made now can be done in quantitative terms. The child should attain a capability such that when presented with a variety of unfamiliar objects, he will be able to classify and order them correctly in terms of prescribed measures.

5. Carrying out the basic operations required to measure area and volume. What needs to be learned is the logic of measurement in terms of units, which will make it possible for the child to equate the areas and volumes of objects having very different appearances. A long narrow rectangle may be equivalent in area to a square. A tall block may be equivalent in volume to a squat one. What are the operations of measurement that make it possible to establish such equivalences? How can an irregularly shaped object be measured? Ultimately, the child should be able to apply these measurement operations to a variety of unfamiliar objects.

6. Understanding and stating numerical equivalences between small and large measures. Small measures like inches and feet can be applied by direct observation, whereas large ones like miles are in a sense extrapolations (involving inferences). The child needs to learn the relationships between the small measures and the large ones. Does the size of a ton have a meaning which can be expressed in terms of operations like those of pounds? What is the size of the earth? What the child should be learning is to make statements which tell how large measures are related to small ones. "What is a ton?" may be answered by the verbal statement, "Two thousand pounds."; but "How would you measure a ton?" is the kind of question which should be answered.

7. Identifying time intervals and methods of measurement of the duration of a variety of events. Can the child learn to identify the orders of magnitude of a variety of common events, such as blink of an eye, explosions, chemical reactions, growth, and many others; and also, know how the duration of such events can be measured? Ultimately, he should be able to do this for a wide variety of physical, chemical, biological, and behavioral events, including those he sees for the first time.

8. Devising and using methods of indirect measurement in situations involving relationships between variables. What are the indirect ways of measuring mass, time, and distance? The child should learn to identify and employ a variety of such indirect measures, such as the unbalanced lever, the amount of solid precipitated as a measure of time, the indirect measurement of distances, etc. Ultimately, he should be able to suggest correct measures in unfamiliar situations, and be able to provide the necessary rationale for them.

9. Devising and using correct measures for inferred variables. For example, Hecht used reaction time of a clam to light as a measure of the inferred photochemical process in the eye. Can the child learn to understand and use such measures of inferred variables? It should be possible for him to learn to do this in a variety of situations that are new to him.

Advanced level. Understanding the properties of different types of measurement scales, and their applicability to a variety of events. What we want the student to understand is the difference between nominal, interval, and ratio scales, and their applicability to various phenomena.

Recognizing and Using Spatial Relations

1. Distinguishing two-dimensional shapes by matching them with their outlines. At the earliest level, the child must learn to match a variety of shapes, both irregular and regular, with their outlines. Beginning with shapes that are widely different, the child can be led to make finer and finer identifications of two-dimensional shapes.

2. Identifying common regular three-dimensional shapes by matching objects which vary in size. The child learns to place in correct categories cubes, spheres, pyramids, oblate spheroids, etc., without necessarily knowing words for them. He should come to be able to do this for an unfamiliar group of objects.

3. Distinguishing nearer-farther, higher-lower, with reference to his own position, and with reference to other positions in space. The child needs to learn to make correct identifications of this sort. Which of two objects is nearer to him, which farther? With reference to a given point on a wall, is another point higher or lower? He should learn to be able to make correct identifications of this sort for any novel situation in which he may be placed.

4. Distinguishing relative sizes of angles in the range 0^o - 180^o. This is nonquantitative knowledge of angular size. Which angle is larger, which smaller? A variety of practice needs to be given, in life-size situations, as well as on paper.

5. Identifying points, straight and curved lines, relative distances, angles, and common shapes such as rectangles and triangles in unfamiliar objects or environments. What points, lines, angles, etc., can be identified in a leaf, a plant, a landscape, or in an unfamiliar machine such as a microtome? The individual should ultimately be able to make such identifications comprehensively and without error. It may be noted that such knowledge supports the acquiring of elementary geometrical knowledge in mathematics.

6. Representing, by rough drawings, points, lines, angles, and two-dimensional shapes (nonquantitatively). The child has to learn to draw such things, as well as simply to recognize them. Can he learn to draw a line from a given point to intersect another line; to draw a triangle through three points, and other simple things of this nature? At this point, it is not a matter of learning precise definitions, which will come at a later stage in mathematics.

7. Representing, by drawing, the two-dimensional projections of three-dimensional objects. How are spheres represented in two dimensions; pyramids; cubes; and other kinds of three-dimensional objects? The child should learn about the projections of three-dimensional objects, and be able to draw them, in an approximate and nonquantitative way.

8. Understanding the relationships (nonquantitative) of relative displacement and direction exhibited in actual examples of simple machines such as the lever, the wheel, and the screw. With what amount of displacement and in what direction does one end of a lever move when the other end is displaced? How far does a wheel travel in one revolution? In what direction does one turn a screw? The child needs to practice making these identifications which pertain to the relationships exhibited in simple machines. He should come to be able to identify these relationships correctly in unfamiliar examples (pulleys, latches, etc.).

9. Understanding the relationships (nonquantitative) of relative forces, velocities, and accelerations in simple machines. Now the child needs to progress to the dynamic aspects of spatial relations. How rapidly does a screw do gownward when it is turned with a given speed? What speed is imparted to a ball at the long end of a lever when the short end is pushed with a given force? The identifications being sought are not quantitative ones, but simply judgments of more-less, slower-faster. Ultimately, the student should be able to make correct judgments of this sort in unfamiliar situations.

Advanced level. Representing the mechanisms for unobservable phenomena. As an advanced objective, the aim is for the child to be able to represent inferred events, such as those of fluid dynamics, current flow, and many others, by means of models. Molecular activity may be a good example.

Drawing Inferences

1. Distinguishing between observed events and inferred states. After having acquired some basic knowledge about observing, classifying, describing, can the child learn to make correct distinctions about the referents of scientific words? He needs to be able to make deliberate distinctions between the observed course of the sun in the sky, and the inferred course of the earth in rotation; between the observed change in an element by burning, and the inferred accretion of oxygen; and many others. Ultimately, he should be able to make this important distinction for any new scientific term, described in ordinary English.

2. Knowledge of various situations which involve the human observer as a system, and various parts of the body as the observed system. Can the child learn to distinguish between light (physical energy outside the observer) and the experience of brightness? What happens to light when it enters the eye? Illusions may be of some importance to this objective, including the moon illusion. Sufficient examples should be provided so that the child is fairly sophisticated about this distinction. For example, he should presumably not be puzzled by the old question about whether a falling tree makes a noise when no observer is present.

3. Knowing and describing the conditions for some of the best-known inferred variables in biology, chemistry, physics, and other sciences. This is a matter of becoming sophisticated about science in general. What is meant by potential and kinetic energy, genes, valences, and many other scientific concepts which are invented by scientists to

make observations into systematic knowledge? The status of these inferred variables in science needs to be made clear, and related across scientific disciplines. The aim here is to make the student capable of using a variety of words for scientific concepts rationally and without confusion.

4. Drawing reasonable inferences about phenomena, and distinguishing them from the observations on which they are based. From a demonstration of chemical change, can the child describe the inferences to be drawn (or which might be drawn), and distinguish them clearly from the directly observed events? He needs to have a variety of practice at this, so that ultimately he is able to do a creditable job of distinguishing and describing inferences for new and unfamiliar demonstrations.

Advanced level. Interpreting unfamiliar phenomena, described in nontechnical language, in terms of reasonable inferences. As an advanced objective, we should like the student to be able to read and interpret an account of a new scientific discovery, in nontechnical language. From such a description, he should be able to tell what the basic observations have been and what inferences are being made.

The Child in the Primary Grades

From one point of view the young child is regarded as naturally a scientist, engaged at the behest of his nature in observing, describing, constant testing, and arriving at conclusions. From this viewpoint, it can be assumed that all one has to do is guide a natural development. From the same point of view science might be broadly interpreted as the natural practice of human investigation. But analytical examination of this idea reveals its inadequacy. A child's natural curiosity and exploratory nature do not really formalize the enterprise of scientific investigation. His curiosity, openness, freedom, and honesty may have a great deal in common with the most sophisticated practice of science which one can describe; but to equate the two as the same is to have little respect for all the steps toward sophistication and knowledge building that will go on in the intervening years from childhood to maturity. Such a simple explanation is unrealistic as a basic assumption in preparing materials and curriculum which will enable a child to grow in the practice of scientific skills and the utilization of scientific concepts.

In the early years the child is not a self-aware, analytical, critical person. In fact he cannot truly be so until he is well beyond the first four years of school life. In loose terms he is an egocentric individual, incapable of handling many logical operations which are fundamental in adult manipulation of the world. As a primary school child he is having to work at imagining or conceiving of objects outside himself, and at being aware of his own thinking and actions. He is still struggling with symbol versus reality, with manipulating symbols as signs, and trying to impose order on the physical world with limited logical equipment. He is engaged in laying the foundation for the two most difficult skills his mind will ever achieve: learning a symbolic system of notation of letters, words, and sentences which will allow him to make statements about real and imagined relationships; and learning notation for number, and the operations which can be performed with these notations.

His curiosity during these years is high and passes through a transitional stage. In the first two grades it is closely akin to the very young child in needing to touch, feel, and sense in various ways the properties of things about him. His wanting to know is satisfied in highly concrete situations rather than abstract ones. Yet on the upper edge of these primary years he is close to more sophisticated patterns of thinking and must be consciously guided toward them.

The young child needs not only to learn skills but to have his curiosity encouraged and magnified. The choice of materials and subjects having innate appeal and high potential value for arousing the needs for desired skills is extremely important. Further, it should be borne in mind that the points of view already expressed about the primary-age child and the origins of science at this age imply that teaching will not proceed as a set routine of memorization and description. The child needs to learn things through his senses, literally to operate on reality. And he needs to do this in as many situations as possible.

Capabilities and Achievements According to Grade Level*

A possible set of capabilities which may be established by a curriculum based upon the sequences previously described is as follows.

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*It should be recalled that this paper was written before the writing of exercises for Science--A Process Approach was started. This part of the paper differs in two respects from the experimental materials now being tried out and to be revised and improved in a third writing session to be held at Michigan State University in the summer of 1965. The differences are:

1. An emphasis on grade levels. As Science--A Process Approach has developed, no grade levels have been designated in the materials. While it is true that in most tryout centers Part One is used in kindergarten, Part Two in first grade, and so on, this is not a requirement. Experimentation on grade and age level continues. The eventual sequencing of exercises will be based on this experimentation. In some centers more of the exercises than those contained in a given part are taught, and in others not all of the exercises in a given part have been taught. Even in the more polished form in which the curriculum will be written and made available for school use, it is not now expected that grade levels will be designated.

2. Reference to achievement in terms of specific content. While some of the specific content herein mentioned has become the setting for process-centered exercises, much of it has not, and instead other topics from science or pre-science provide the setting for exercises with a primary objective to teach one of the processes of science.

Kindergarten

The child leaving kindergarten and entering first grade should be able to identify many objects and classify them especially with regard to likenesses and differences in physical characteristics: color, size, shape, weight, texture, smell, and taste. He should be able to distinguish among the senses and relate these distinctions to qualities in an object outside himself.

Further, he should be able to classify many common objects with regard to what they do and how they relate to specific situations: what floats, what attracts a magnet, what melts under certain conditions, what changes color and when, and what changes form. In this instance he should know something about everyday common forms of matter: ice, snow, water, steam; granular, dissolved, precipitated. He should be aware of and be able to make visual choices on charts and diagrams about the daily weather and observable phenomena; such as, sun, rain, snow, clouds; temperature in terms of how it feels and what it does.(freeze ice, sour milk, etc.).

He should be able to utilize a complex of classifications about various kinds of things which cause other things to move: food in animals, electricity in appliances, gas in cars, steam in trains, batteries in flashlights and toys, magnets in size-related metal objects.

He should be able to classify comparative aspects of environment as to near and far, up and down, here and there, in the neighborhood where he lives. He should achieve an orientation and mapping of his room and home territory. He should be aware of dark and light, and of the relationships of the sun and moon to day and night. He should be able to classify and name the gross aspects of his physical environment: sky, air, water, earth, soil, sun, and moon. He should be able to make gross distinctions about time intervals and know how they are measured: the calendar and clock.

He should be able to count, at least to ten, and to assign numbers to a variety of groups of objects. He should distinguish number and the symbol for number, and have some experience in separating the object from symbol.

In short, the child in departure from kindergarten should have come into contact, on an experiential level, with a multiplicity of situations, all of which have offered opportunity for him to observe, classify, and communicate about the world in as precise terms as are possible at his age. It should not be assumed that, because he can perform the operation in one situation, he can do so in others; he should actually perform in a variety of situations.

Grade One

As the child leaves the first grade he should be able to carry out much more complicated operations on some of the phenomena he approached in kindergarten. In addition to being able to read and interpret symbols both in letter and number, he should be able now to write down and describe on a simple level the names and attributes of some common objects. He should be able not only to distinguish big and little objects from among a series, but he should be able to assign symbols to reflect the comparisons and organize them in a practical way.

He should be able now not only to put together, out of a heterogeneous collection (as of rocks), those which are alike in one way, but he should be able to recombine these into other sets on the basis of likenesses or differences. He should be able to apply general class names to many aspects of the ordinary environment: furniture to many objects in the room; animals to a wide variety of living things. He should be able to distinguish between sets which are fairly obvious and intuitively delimited, such as "all cats," "all dogs," "all monkeys."

He should be aware not only of what makes things go, but should be talking and dealing with what goes the faster, rockets or cars, jet planes or planes with piston engines. He will be interested in which goes faster a toy car down a steep plane or one down a gentle slope. And he should be able to devise his own simple measurement basis for these. He should be able to operate and build devices which make things go faster or make work easier. He should know something about the descriptive conditions for life in himself and in animal pets.

He should be able to distinguish angular direction in space and identify lines, planes, and angles in complex objects. He should be able to add and subtract, and should be able to use these skills operationally on a few measurements of movement or intensity in the classroom.

Grade Two

The child should leave this grade with many skills consolidated at a new level. He should have learned to use common measurement instruments, to deal with area and volume, numerical equivalence, scales and units of measurement and he knows the relationship of points, lines, and angles in a descriptive sense. He should be able to make rough two-dimensional drawings of three-dimensional objects. He should be able to identify various time intervals, and understand what events are in terms of rates of change.

He will have by now followed up on weather and descriptive seasonal observation, relating it now to the movement of the earth about the sun. He should now read well enough to begin to fill in descriptive details about the world as science sees it.

He should be able to further relate events, not merely the sun to seasons, but life to the presence of food, water, air, and specific conditions. He should think, for example, about magnetism in a new light, as an interaction force that is found in other places than just the two magnets he manipulates. He should be able to entertain the idea of its existence in the earth, and in the universe.

He should begin to use other than obvious physical means for classification; that is, apply certain tests of hardness to rocks and make statements about events, and consequent likenesses and differences among them.

Further, he should be able to see and describe out of his own experience the relationship between kinds of animals and the environments in which they live. He should be able to describe relations between obvious adaptive features and the ways animals get a living.

Grade Three

By the end of this grade, the child will have taken some important steps forward in describing and inferring events. He should be able to distinguish observed and inferred events and can analyze a system in terms of observer, direct and distant interaction, strength of interactions and relationships.

He should be able to begin to talk meaningfully about experiments, and engage in simple ones, finding it easier to be objective and to assume the conscious role of observer and experimenter.

He should now begin to conceive of large size, great distances; and the earth and the universe should take on new meaning. He should progress, for example, from awareness of magnetism in many places to making actual measurements on earth magnetism with models, the compass, and relate these to map reading. He may now spontaneously question how we know the earth is round, and should be able to engage in proving this.

He should be on the threshold of an age when his curiosity about natural events will be at its peak. He begins to read widely and may tend to assimilate uncritically. He may be amazed by the distant, and far away in time, the largest and the smallest. Questions, open-ended explorations, mystery, and unsolved problems should enchant him, and should continue to do so even more as he moves into the fourth year and above. And in these he will gradually emerge, if he has been properly directed, into the individual insights and concepts that are the foundation on which genuine understanding of science and its more complex processes may be built.

May 29, 1963

THE SCIENTIFIC APPROACH TO KNOWLEDGE

A working paper prepared for the 1964 summer writing conference, Stanford University.

The first four parts of Science--A Process Approach, developed by the writing groups of the AAAS Commission on Science Education, provide instruction in science for the grades kindergarten through third, emphasizing the development of competence in basic skills of importance to further science learning. These processes are called Observation, Numbers, Measurement, Space/Time Relations, Classification, Communication, Prediction, and Inference. The child is introduced to a variety of content in acquiring these skills--he learns about plants and animals and rocks and weather and solutions of chemicals and the motions of objects. The content he learns is not systematically related to particular scientific disciplines, but is considered to be derived from more or less familiar objects and phenomena in the world around him. It may be said that at the end of the third grade the child who has been instructed by means of these exercises has acquired some important fundamental process skills, a good many basic scientific concepts, and some organized knowledge about the natural world.

What should be the next steps for science instruction? What is the desired nature of instruction in science for grades four and five? The answer to these questions should, in all probability, take into account three things:

1. the objectives that have been achieved by this set of materials through the third grade;

2. the possibilities of further building upon and elaboration of these valuable process skills, in aiming at the ultimate goal of science understanding and "literacy";

3. the expectation of what advanced instruction in the junior high school may be like when based upon such a comprehensive foundation.

This paper proposes to discuss these questions in reverse order.

What Will Junior High Science Be?

In general, it is considered probable that the background of both process and content knowledge imparted to the student by means of the AAAS "process approach" will be considerably greater than any now in existence. It should be possible to test the truth of such a statement empirically at some time in the future. But the expectation is clearly there. This approach to science instruction is designed to develop competence in carrying out the activities relevant to science. In this sense it differs from most traditional instruction (as exhibited, for example, in most elementary texts for these early grades), which appears designed mainly to establish verbal knowledge of science of a rather unsystematic sort.

In view of this difference in approach and its expected result, it seems reasonable to suppose that by the time junior high grades are reached, the student will be able to engage in the study of various topics of science which are ordinarily considered a part of such disciplines as biology, chemistry, physics, geology, psychology, astronomy, or some other science, as related to the logical structure of each. The only qualification on this statement may be in the degree to which advanced forms of mathematics such as the calculus must be omitted. (This is not considered an extremely serious limitation, since many college science courses must now be given in this way.) It would seem to be a reasonable aim to eliminate the notion that there should be topics of "junior high chemistry" which are somehow different from those of "senior high chemistry" and "college chemistry," in the sense that they are "watered down."

A number of efforts are currently being devoted to the preparation of science materials for the junior high grades--in physical science, earth sciences, and biology, among others. Thus it may be expected that there will be attempts to use what are considered rigorously developed instructional materials in many of the sciences in junior high schools if not in all of them. It may be noted that some effort is also being devoted to the planning of different arrangements of content of science courses for the junior high, some of which will cut across disciplinary lines. The trend of these developments is clearly in the direction of having the student begin the study of topics and theoretical structure of the scientific disciplines, whether in an integrated fashion or otherwise, in junior high school.

Building Upon Process Skills

We assume that children who have completed the first four parts of exercises on scientific processes have developed a number of important competencies. In brief, they are able to observe, distinguish, and recognize the important physical properties of objects and their variation along these dimensions. They can make systematic observations of events and the relationships of successive events, such as that between a rolling ball's weight and its amount of push. They are able to make classifications of objects along various dimensions. They can devise and use arbitrary units of measurement, as well as standard ones. They can deal with quantities, in the sense of counting and adding. They are acquainted with distances, directions, and magnitudes, and can construct simple graphs of phenomena such as the growth of a plant. They have a certain amount of skill in describing things and events accurately, and know how to communicate to others what they observe. They have learned the idea of prediction from one set of events to another, and can distinguish between an observation and an inference.

Although these are obviously important skills, they have not yet been "put together" to any substantial degree in carrying out extended, integrated activities which resemble the work of a scientist or science student. Presumably, this is what they need to do next. There are two major reasons why these more comprehensive activities of science need to be undertaken. First, the individual process skills must be practiced in a manner which demands their integration in order to insure that they will generalize (or transfer) best to the systematic planning, observation, experimentation, and communication which a concrete understanding of science implies. Second, the use of simpler skills in performing higher-order integrated scientific tasks appears to be one of the best ways to insure their retention.

It appears, then, that the best way to achieve the generalization and retention of "process" skills is to continue to provide for a kind of "process" emphasis in instruction. However, at the fourth and fifth grade level, such an emphasis can build upon simpler competencies to design instructional exercises which are at once more complex, more comprehensive, and more nearly like the kinds of activities engaged in by a scientist when solving a problem. They can instruct students in the scientific approach to the generation of organized knowledge. They need to deal with such integrated activities as hypothesis forming, operational definition, variable control and manipulation, experimenting, model building, and the interpretation of data.

The Competencies Established in Grades K-3

In order to describe in concrete terms the kinds of things students who have completed Parts One through Five of the AAAS materials can do, we summarize here, first, the knowledge of processes which has been established, and second, the concepts which have been learned. Both of these will be useful for continuing instruction in scientific activities. Both become a part of the continuing process of science education which leads to an ever-deepening understanding.

Processes learned. The knowledge of processes can be revealed by the kinds of things a third grade child will be able to do as he completes the exercises in Part Four of *Science--A Process Approach*. Obviously, each of these implies that he can do many more simple things which he learned via the exercises in the preceding volumes. It is also recognized that a certain amount of forgetting is inevitable, and the necessity of making provisions for review of previously acquired process skills should not be overlooked.

1. Systematic observation. Observing relations under conditions in which one or more physical properties is systematically varied.

2. Standardized measurement. Identifying, recognizing, and naming the length, width, volume, temperature, and weight of objects as well as time intervals using standard units of measurement. The presentation of measurements by means of a bar graph.

3. Numbers. Describing the sum and product of two digit addition and multiplication by means of verbal and written number sentences.

4. Space/Time. Identifying and recognizing the effects of motion as they apply to dimensions of effort, distance, direction, time, and appearance.

5. Systematic classification. Devising classifications of collections of objects by means of single or multiple dimensions such as state of matter, color, volume, symmetry, area, and weight.

6. Inference. Making reasonable inferences from observed events, and distinguishing between an observation and an inference.

7. Prediction. Making and testing a prediction of a specific outcome based upon an observed set of events.

8. Communication. Communicating a series of observations from one individual to another by means of one or more of the following: oral and/or written descriptions of changes in physical state, motion, color, weight, volume, and area; written descriptions of quantitative measurements using standard units of length, area, and volume; presentation of observed data through bar and point graphs.

Concepts learned. A fairly substantial number of scientific concepts will have been learned by the children who complete Parts One through Four. By knowing a concept is meant that the child can respond appropriately to the word. For example, if one says, "Compare the volume of these two cylinders," the child should respond by carrying out an operation which is appropriate to volume, and not to height, area, or some other concept. To say that a concept is known does not necessarily imply that it is known with complete thoroughness and precision, for that would be too much to expect. What is implied is that the resulting action, verbal or otherwise, is appropriate to the concept and not confused with any other concept.

The concepts with which the children may be expected to have some familiarity can be identified from the vocabulary lists in the exercises. Again it should be emphasized that the child will respond correctly to the names of these concepts; this does not mean he can "define" them. But it should be possible to use these words in subsequent instruction by having the child remember them, rather than by introducing them as if initially.

Approach to Preparation of Materials for Grades 4-5

In preparing materials for grades K-3, members of the writing team undertook assignments organized around processes, using whatever science content was convenient or relevant. It is proposed that the procedure for grades four and five begin with assignments on representative content. In undertaking to begin in this fashion, however, we need to heed a clear warning not to stray from the purposes of continuing the "process approach." Although the content is representative, it is still subordinate to process. The goal is to provide instruction in the more complex and integrated process activities described in the next section. The objective of each exercise, and the appraisal of this objective which accompanies it, should be conceived in terms of processes. The question to be borne in mind is still of the sort, "Has the child learned to formulate hypotheses?" rather than "What does he know about the atmosphere?"

Activities in Learning the Scientific Approach

First of all, the additional learning for grade four and five should continue to emphasize and elaborate the process skills developed in the earlier grades. The kinds of integrated scientific activities which will build upon previously learned skills and concepts, and which seem appropriate to the aim of acquiring the scientific approach to knowledge, are as follows:

1. Making operational definitions. The importance of this activity is apparent to every scientist. For example, if one proposes the hypothesis that learning requires attention, one must then undertake to define both "learning" and "attention" in such a way that another person can identify these events in terms of operations. It is quite unsatisfactory, for example, to say that attention means "mental concentration" (a common student response); this phrase has not been operationally defined. A number of operational definitions of "attention" would be possible; for example, "an individual is attending to a familiar object in a visual scene if he is able to state correctly the presence or absence of the object immediately following the disappearance of the scene." For another example, an operational definition of "mass" is "that property of an object which determines the amount of acceleration that will be imparted to it by force of a given magnitude." Practice in formulating operational definitions of suitable degrees of complexity can be expected to contribute greatly to the student's knowledge of the processes of science.

2. Formulating hypotheses. The objective of such instruction is to make the student capable of formulating reasonable hypotheses. He should be able to distinguish the hypothesis he makes from the observations from which it has been drawn, and also from the observations required to test it. The latter requirement implies that the student is able to make operational definitions of the "intervening variables" which form a part of his hypothesis. As the term hypothesis is used in Science--A Process Approach a hypothesis is a general statement. For example, if a pupil has found that a copper wire is a good conductor of electricity, and that it is also a good conductor of heat, he might make the inference that a pair of scissors which is a good conductor of electricity also is a good conductor of heat. He tests this inference and finds that the inference is supported. Then he may state: "All good conductors of electricity are good conductors of heat." This statement is a hypothesis. Of course he cannot prove that a general statement (a hypothesis) is true, but by conducting many tests he may be able to show that the hypothesis is strongly supported.

3. Controlling Variables. To a large extent, the student's previous study of science has emphasized the systematic observation of naturally occurring events. But he should now begin to learn that he can make observations under conditions that he deliberately sets out to control and manipulate. For example, if he wishes to study the effect of amount of light on plant growth, he must plan deliberately to place a set of

identical plants under conditions in which other variables are deliberately kept constant, and light is deliberately varied. Obviously this kind of activity grows out of his previous learning about systematic observation, and leads into the performance of experiments.

4. Interpreting data. The proper interpretation of data, in ways which will at once get the most out of them, and at the same time avoid over-generalizing, is another important scientific activity. A background for the learning of acceptable performance in data interpretation has been provided by previous experience in inference and communication, as well as by the substantial learning of concretely based concepts. We should like the student to be able to draw imaginative and comprehensive conclusions from scientific data, and also to avoid drawing conclusions which are unsupported by data, or which fail to take account of alternative explanations.

5. Experimenting. The planning, execution, and communicating of simple experiments is surely not too much to expect of children who have had the advantage of the process approach to the learning of science. However, simple experiments are not easy to design, since they can so easily go beyond the store of knowledge possessed by the child. The attempt to get the student involved in experimentation nevertheless deserves being made. There must be some amount of structuring of these experiments, if the learning they generate is to be of dependable value. It is a challenge to the designer of such exercises to avoid the "cook book" character of old fashioned "laboratory work," while at the same time requiring the student to formulate the problem, think out this procedure, make his observations, and draw his conclusions.

The Problem of Content

As previously pointed out, the volumes of Science--A Process Approach cover a variety of content, from many of the scientific disciplines. Some disciplines may be given more emphasis than others, but if this is so, it was not planned that way.

The course of development of exercises emphasizing processes requires considerable discipline of thought among the scholars assembled as a design team. In particular, they need to be constantly on guard that they are not injecting their own specialized interests and enthusiasms for their own subject into the exercise being developed. The "process approach" is one which subordinates the acquiring of verbal content knowledge to the gaining of process skills. A chemist may say to himself, "It would be wonderful if these students could learn about molecular weight; then they would not have to learn it in high school." If he thinks too hard along these lines, he is likely to end up trying to teach first graders about molecular weights.

But this is not the process approach, and will not accomplish what this approach is intended for. We do not want to teach "first grade biology," "second grade physics," and so on, because it is believed that such knowledge is bound to be incomplete, shallow, verbally parroting, and highly ineffective for the later learning of the separate scientific disciplines. What the chemist (in our example) should be aiming for in designing learning exercises for the elementary grades is this: Teach the student to be so competent in the processes of science that when he ultimately learns about molecular weights he will learn rapidly, without confusion, and with a profound comprehension. He will not be disturbed by the fact that "he can't see it;" he will not tend to confuse it with atomic number; he will immediately understand its relation to molecular structure; and so on. The process approach is designed to make possible the rigorous study of science by people who don't have to be told "what science is," "what observation is," "what a hypothesis is," and all the rest of these fundamental ideas which should be valuable parts of their general education.

In any case, the problem of choosing proper content is always present in designing instructional materials for science. In looking toward the development of material for the fourth and fifth grades, it would seem desirable to make an attempt to be <u>representative</u> of all the scientific disciplines. This does not imply a departure from the emphases on scientific activities described in the previous section. But considering the aim of getting the student ready to undertake the serious study of science as a discipline in junior high school, some attention needs to be paid to the scope and variety of exercises being designed, insofar as their content is concerned.

Since the material to be developed must <u>sample</u> content, it seems reasonable to arrive at a representative sample by listing certain <u>key ideas</u> of the various sciences. These will provide an additional framework for the student's later study of the individual sciences topic by topic, and will thus be of some aid to subsequent learning. In biology, a key idea might be <u>the diversity of living things</u>; in physics, <u>forces and interactions</u>; in chemistry, <u>the structure of matter</u>. Some of these will doubtless exhibit overlapping among traditional disciplines, and this is of course not undesirable.

<u>Key Ideas of the Sciences</u>

A set of broad topics reflecting some key ideas of the scientific disciplines, and representative of the broad range of content of the sciences, were listed as follows:

The structure of matter
Energy, its forms and transformations
Varieties of forces and their interactions
The universe, its structure and components
Relationships between variables; graphing
Descriptive statistics and probability
Rational numbers
The diversity of living things
Growth and development
Behavior of living things
The flow of energy in nature
Geologic change
Climatic change

Summary of the Proposed Approach

The proposed approach to the development of grade four and five materials on the scientific approach to knowledge may be summarized as follows:

1. Select as a content topic one of the key ideas of science listed above.

2. Be as thoroughly acquainted as possible with the previously used process skills listed in a previous section, and illustrated by exercises of Parts One through Four. Writers should pay particular attention to achieving an orderly integration of newly written topics with those which have preceded them.

3. Plan a scientific exercise to give the student an opportunity to learn to carry out any one or several of the processes of formulating hypotheses, making operational definitions, controlling and manipulating variables, experimenting, formulating models, and interpreting data. Such exercises should also be conceived as reinforcing previously used simpler processes.

4. Remember to include an appraisal at the end of each exercise or part-exercise. This asks the student to do something he has not done before, so it is in a sense a new exercise. It is designed to measure his competence in the processes taught.

Another Requirement

There is believed to be still another requirement for instruction in science, which the preceding approach will not fully satisfy. It is described here at the end, because it is also thought that it cannot be undertaken by a "writing group." Serious consideration needs to be given to it, though, and to means for accomplishing it as an objective.

An obvious need is for science students in the elementary grades to know a great deal about the world they live in. The many things they want to know cannot all be experienced directly. Science needs to become part of their general knowledge, as well as a means of solving problems and a way of viewing natural events.

What is meant by the universe? What is an atom? These are simply two examples of the kinds of questions young people ask about science. Needless to say there are many more which derive from their incidental knowledge of technological advances. The answers to such questions need to be supplied with as much accuracy and imaginativeness as possible. The child needs to know in a general, philosophical way what the scope of science is and what scientists do. Of course, a lot of this he can learn incidentally. Yet this method seems rather undependable and risky if one is concerned about "scientific literacy" and about "positive attitudes toward science."

At the time of the fourth grade, the child has learned to read. He should read about science and scientists. Perhaps he should gain from his reading a "literary" knowledge of the great themes of science, such as "life on earth," "earth, sun, and planets," "how things change," "science and work." Another possibility is for the student to read about the great ideas of science, such as the discovery of oxygen, the idea of the vacuum, the circulation of the blood, and so on, perhaps in the historical manner advocated by Conant. Still a third kind of reading which might be done is about scientists and their work.

The important characteristic such reading matter needs to have is that it should emphasize and exploit the student's previously acquired knowledge of the processes of science. Since he has learned to do these things, the student can now read about them with great profit--they do not have to be hidden from him or "explained" to him.

It seems likely that few books on science are currently written from this point of view. After all, a writer cannot assume knowledge of the processes of science even in the average (non-scientist) adult. But the reading of books represents another way this early process knowledge should be built upon and elaborated. The extablishment of the desired attitudes is probably critically dependent upon reading the proper books at this age.

Planning should be undertaken to explore ways in which such books on science might be written.

May 1, 1964