DOCUMENT RESUME

ED 182 143 SE 029 859

| | |
|---|---|
| AUTHOR | Champagne, Audrey B.; And Others |
| TITLE | Content Structure in Science Instructional Materials and Knowledge Structure in Students' Memories. |
| INSTITUTION | Pittsburgh Univ., Pa. Learning Research and Development Center. |
| SPONS AGENCY | National Inst. of Education (DHEW), Washington, D.C. |
| REPORT NO | LRDC-1978/22 |
| PUB DATE | 78 |
| NOTE | 59p.; Not available in hard copy due to small print throughout entire document |
| EDRS PRICE | MF01 Plus Postage. PC Not Available from EDRS. |
| DESCRIPTORS | *Classification; *Educational Research; *Geology; Grade 8; *Instructional Materials; Junior High Schools; Science Course Improvement Project; Science Education; *Scientific Concepts; Secondary Education; Secondary School Science |


ABSTRACT

The research reported in this paper concerns the design of instructional materials that represent the content structure of a science discipline and the development of methods of probing and representing the knowledge structure in a student's memory. The science discipline selected for the study was geology. Specifically, the conceptual structures and related taxonomy for classifying rocks were used in the instructional materials designed for the study, which consist of a segment of the field-testing version of the Individualized Science (IS) program. Thirty students from an eighth-grade class in a parochial elementary school were selected for the study. None of these students had previously received instruction on minerals and rocks. All had previously studied IS units, however, and were thus familiar with the mechanics of the instructional materials. A preinstructional concept structuring task was administered to probe for students' knowledge about rocks and minerals. A pretest on concepts in descriptive geology was then administered. Instruction followed. Posttest and postinstructional concept structuring task administration occurred after instruction. Test results were analyzed in detail. Implications for the administration of probing tasks are discussed, particulary for applicability in instructional techniques and determination of content difficulty for particular students. (CS)

# LEARNING RESEARCH AND DEVELOPMENT CENTER

1978/22

## CONTENT STRUCTURE IN SCIENCE INSTRUCTIONAL MATERIALS AND KNOWLEDGE STRUCTURE IN STUDENTS' MEMORIES

AUDREY B. CHAMPAGNE, LEO E. KLOPFER,
ALPHONSE T. DeSENA, AND DAVID A. SQUIRES



University of Pittsburgh

# CONTENT STRUCTURE IN SCIENCE INSTRUCTIONAL MATERIALS AND KNOWLEDGE STRUCTURE IN STUDENTS' MEMORIES

Audrey B. Champagne, Leo E. Klopfer,
Alphonse T. DeSena, and David A. Squires

Learning Research and Development Center

University of Pittsburgh

1978

The research reported herein was supported by the Learning Research and Development Center, University of Pittsburgh, funded in part as a research and development center by the National Institute of Education (NIE), United States Department of Health, Education, and Welfare. The opinions expressed do not necessarily reflect the position or policy of NIE, and no official endorsement should be inferred.

# CONTENT STRUCTURE IN SCIENCE INSTRUCTIONAL MATERIALS AND KNOWLEDGE STRUCTURE IN STUDENTS' MEMORIES

Audrey B. Champagne, Leo E. Klopfer,
Alphonse T. DeSena, and David A. Squires

Learning Research and Development Center
University of Pittsburgh

The research reported in this paper concerns the design of instructional materials that represent the content structure of a science discipline and the development of methods of probing and representing the knowledge structure in a student's memory. The goals of this study are: (a) to assess the congruence between science content structure represented in science instructional materials and knowledge structures of that science content in the student's memory, and (b) to determine how student knowledge structure representations change as a result of instruction.[1]

## Science Content and Knowledge Structures

The conceptualization for the present research derives most immediately from the work of Sha elson and Stanton (1975). Central to Shavelson's approach and ours are two assumptions. One is that:

---

[1] A second goal is to identify components necessary for the design of instructional programs to teach problem solving to students at the elementary and middle school levels. A third goal is to analyze the macrostructure of science instructional materials to determine the way in which the content structure of the science disciplines is represented in the instructional materials. Further discussion of the project's long-term goal and related concerns may be found in the Learning Research and Development Center Technical Proposal (1977), pp. 32-42.

> A structure of a subject matter, ultimately, rests in the minds of the "great scientists." This structure is communicated through the scientists' writings in journals and advanced textbooks as well as through informal communication channels. (Shavelson, 1974, p. 232)

The second is that a knowledge structure may be conceived, at least in part, as a network of concepts and relations between concepts in memory. These two assumptions had important implications for the conceptualization and design of this study. In fact, assumptions we made about the relationships among the structure of a natural science discipline, knowledge structures of experts in that science discipline, and the content structure of the scientific writing of experts were significant both in designing the instructional materials and in setting the standard against which student knowledge structure representations would be judged.

From the scientific writing of experts in geology, we made inferences about the structural characteristics of the discipline of geology. These structural characteristics were incorporated into the instructional materials used in the study and into the knowledge structures we constructed as standards against which to judge the knowledge structure representations generated by the students. Since no empirical means of determining the content structure of written science materials currently exist, there is no way of measuring how well the content structure of our instructional materials matches the content structure of scientific writing by experts. However, indirect evidence was obtained through expert review of the instructional materials by three university geology professors who agreed that the content of the materials successfully maintained the scientific integrity of geology.

Determination of the Knowledge Structure Standard

Two alternatives were available in setting the standard against which student knowledge structure representations would be judged:

(a) to proceed empirically and obtain representations of knowledge structures from a number of people knowledgeable in geology and then identify characteristics common to their structures; or (b) to refer to the scientific writings of experts in geology and infer the discipline's structure from their writings.[2] For the purpose of this study, the second alternative was chosen, thus maximizing the probability that there would be congruence between the content structure of the instructional materials and the standard knowledge structures. This decision was consistent with one goal of our research, viz., to determine how student knowledge structure representations change as a result of instruction.

In the process we used to determine the standard structures and assess the congruence between the content structure in the instruction and in the writing of experts, it was assumed that a knowledge structure is, in part, a network of concepts and relations between concepts. In selecting the particular concepts to be included in the instruction, and later in the standard knowledge structures, judgments were made about their relative importance in the discipline structure of geology. The concepts selected for inclusion were those that appeared frequently in the writings of experts and that are central in current conceptual structures of geology. This process required attending to many constraints, one of which was the reality that the instructional materials were being designed for middle school students and, therefore, could not contain some of the more abstract concepts and formal relations incorporated in the scientific writings of experts in geology.

---

[2] Useful discussions of the notion of structure of the discipline are contained in the records of two conferences in which Schwab was an instrumental participant; see Schwab (1964), and Ford and Pugno (1964).

We have not specified formally how decisions about the importance of concepts and conceptual structures of geology were made. The process may be clarified by means of one prominent illustration related to the ways in which geologists classify rocks. When geologists or other scientists classify objects in accordance with the prevailing ideas of the science discipline, they are doing much more than sorting things into groups. The particular scheme of classification that is commonly used by the practitioners of a science at a given time reflects the principal theory or beliefs concerning the science's domain at the time. Thus, for example, when a geologist's classification scheme for rocks displays three principal groups--igneous, metamorphic, and sedimentary--it displays at the same time a fragment of the current theory, i. e., a part of the conceptual structures of physical geology. Since we are concerned about displaying aspects of the conceptual structures of physical geology in our instruction, a classification scheme for rocks becomes a prime candidate for inclusion.

In the writings of geologists, one can find several different schemes for classifying rocks. Each of these schemes is based on a conceptual structure of geology. Since the conceptual structures of geology are interrelated, the classification schemes are also interrelated. For example, geologists classify rocks on the basis of (a) chemical composition, (b) crystalline structure, and (c) the rock cycle. Each of these conceptual structures and its related taxonomy of rocks appear in the instructional materials designed for this study and in the concept structuring tasks we administered to students. Although the relations among the conceptual structures are a part of instruction, these interrelationships were not part of the concept structuring tasks used in the study.

## Design of Instructional Materials

The instructional materials used in this study deal with the subject of minerals and rocks and consist of a segment of the field-testing version of the Lyell Unit of the Individualized Science (IS) program.[3] The Lyell Unit includes aspects of historical and physical geology; the Invitation to Explore (ITE) Minerals and Rocks is primarily descriptive physical geology. The Table of Contents of the ITE Minerals and Rocks, which is reproduced in Figure 1, indicates the scope and sequence of topics and activities. The student's booklet for the ITE is 67 typewritten pages long and consists of reading text, manipulative activities (see Explorations A through H in Figure 1), and student self-administered progress tests. On the average, a student completes the ITE in three to four weeks with five 45-minute periods per week.

ITE Minerals and Rocks was designed to incorporate structural features of the content of descriptive physical geology. The structural features include hierarchical class-inclusion, transformational, and definitional relations. Certain of these relations are evident in the ITE's Table of Contents (Figure 1), which shows that the ITE is organized in part around (a) the definition of a mineral, and (b) the

---

[3] Individualized Science is a basal science program intended for use in school grades K through 8 and consists of a complete science curriculum integrated with an individualized learning management system (Champagne & Klopfer, 1974). The IS program is designed to enable the child to acquire a foundation of scientific literacy and to become skillful in using the processes of scientific inquiry. The program encourages open-ended student investigations that are designed to develop a student's skills in using the processes of scientific inquiry and problem solving. One way in which this is done is through the use of a type of instructional resource called "Invitation to Explore" (ITE). A series of these ITE's appears in certain instructional units of the IS program. However, most of the ITE's can be used independently of the IS program's unit where they appear and, in that case, the ITE functions as a self-contained instructional module.

TABLE OF CONTENTS



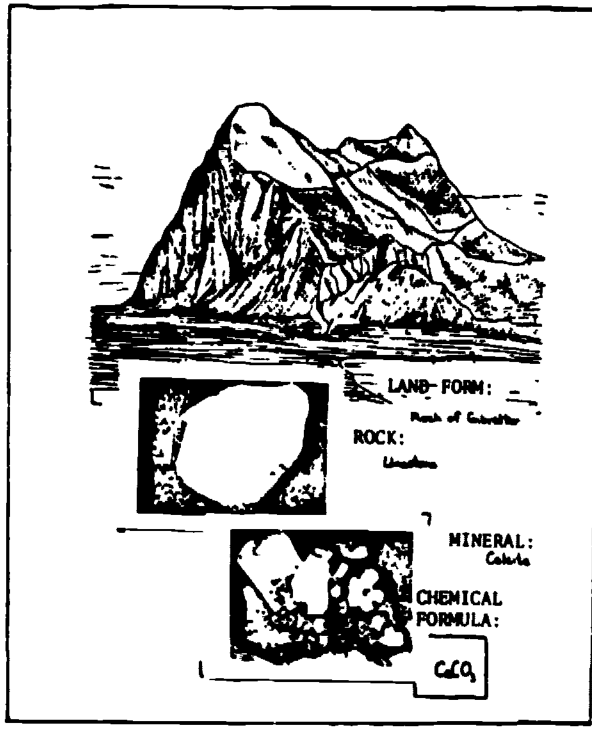
Figure 1. Content page of the ITE Minerals and Rocks

taxonomic classification of rocks. The two most emphasized structural relations, one hierarchical and the other transformation, are discussed later in this paper.

The ITE begins by setting a structural context for the student. The content structure is described in the text and is represented visually with a drawing (see Figure 2) that illustrates both the hierarchical relationships among major concepts and examples of the concepts. The introductory narrative summarizes these relations. They are elaborated on throughout the text of the ITE. Transformational relations are another major structural feature of the ITE. This structural feature, illustrated in the excerpt from the ITE in Figure 3, is also represented in the text. The design of instruction in the ITE Minerals and Rocks was executed with structural principles explicitly in mind to facilitate the student's learning and retention of the science concepts.

## Design of the Concept Structuring Task

The form of the concept structuring task developed for this study allowed us to get information both about the way students order concepts in memory and how they perceive the relationships between the concepts. In this procedure, the knowledge structure is derived via an analysis of the properties of the groupings of cards made by students. (On each card is printed a single word or concept. Each set of cards contains a range of concepts central to a particular subject-matter area--in this instance, descriptive geology.) We used this card-sort procedure in an exploratory study from which we learned that simply having students sort concepts into groups provided no information about the students' conceptualization of the sorting process. We began, therefore, to question students in an unstructured way to determine why they had sorted the concepts as they had. It then became apparent that students could often make discriminations




The Rock of Gibralter is a landform made up of limestone rock. Limestone is a mixture of different minerals, but most of it is the mineral calcite (KAL site). Calcite is a naturally occurring chemical substance that contains molecules of calcium carbonate. The chemical formula of calcium carbonate is, $CaCO_3$.

Figure 2. Example of description and illustration of the content in the ITE Minerals and Rocks (pp. 4, 5).

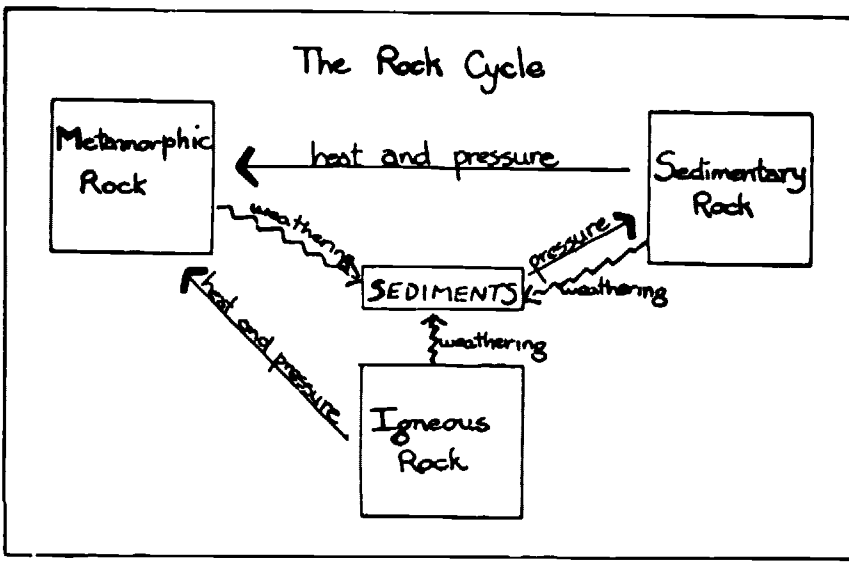



Figure 3. Transformational relationships among rocks as illustrated in the ITE Minerals and Rocks (p. 57).

between certain terms to a greater degree than the presented task allowed and that the "unstructured" questioning which probed for these discriminations ought to have been more structured. Further, our examination of systems of text analysis, with their detailed specifications of structural relations in textual material, led to our finding value in experimental methods that probe more deeply into relations between concepts.

As our conception of structure and its implications for instruction and learning developed, the card-sort method appeared less adequate to our needs. Consequently, we designed the Concept Structure Analysis Technique (ConSAT), which has become an important instrument in the conduct of our research. The inspiration for this technique came from the research of two cognitive psychologists, Paul Johnson (1964) and Richard Shavelson (1974). Both of these investigators sought ways of determining how individuals relate science concepts in memory. Our ConSAT is an extension of the card-sort technique, a method which Shavelson used to investigate this question.

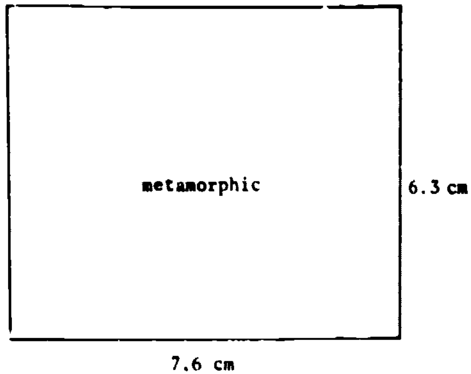
In our research using the ConSAT, each concept structuring task is administered on an individual basis in the following manner. After introductions and small talk, the researcher tells the student, "We are trying to find out how students think about words used by scientists." The researcher hands the student a stack of cards and asks the student to read the words on the cards and to sort them into two stacks. One stack of words contains those the student recognizes (has seen or heard before). Words that the student does not recognize are put into the other stack.

The unrecognized stack is set aside. The researcher then asks the student to arrange the recognized words on a large piece of paper in a way that "shows how you think about the words." While completing the arrangement, or after its completion, the student is asked to tell why the words are arranged as they are. As the student points out relationships between the words, the researcher connects the related words or groups of words with a line and then labels the line with the relationship that the student gives. The researcher also asks questions about the arrangement of words on the paper when the student does not volunteer information. The students often change a card from one position to another. The researcher encourages this and asks questions about the change, while noting the change and other relationships. Finally, the student is asked to go through the stack of unrecognized words and make a final attempt to fit them into the structure already produced. (The terms used in the concept structuring tasks for the present study are listed in Figure 4.)

The arrangement of the words on the sheet of paper and their recorded relationships serve as the input data for the analyses of student knowledge structure representations in the ConSAT. As we have indicated, these analyses essentially consist of making comparisons between the students' representations and standard knowledge structures. When concept structuring tasks are administered prior to and following instruction and the ConSAT is applied, we can obtain a measure of changes in student knowledge structure representations, changes ascribable to the instruction. In the study described below, we utilized the ITE Minerals and Rocks as the instructional materials and obtained measures of how student knowledge structure representations changed from pre- to postinstructional administrations of concept structuring tasks.

## Setting and Sample Population

Our study was carried out in a parochial elementary school, located in the Mount Washington area of the city of Pittsburgh. The school's approximately 400 students in grades K through 8 come from middle-class Catholic homes in the immediate neighborhood. Science classes met in a large room in the basement. There were 30 students




**Practice Task**

- body
- ears
- eyes
- face
- foot
- heel
- metatarsus
- nose
- soul
- toes

**ATOM Task**

- atoms
- chemical compounds
- chemical elements
- chemical substances
- molecules

**MINERAL Task**

- C
- $CaCO_3$
- calcite
- calcium carbonate
- carbon
- diamond
- graphite
- halite
- inorganic solid substances
- limestone
- mineral
- NaCl
- shells of sea animals
- substances with a characteristic crystalline structure
- substances with a definite chemical composition
- naturally occurring substances
- table salt

**ROCK Task**

- granite
- igneous
- lava
- limestone
- magma
- marble
- metamorphic
- pumice
- rock
- sediment
- sedimentary
- shale
- slate

Figure 4. Sample card and words used in concept structure tasks.

in each class. The teacher used the IS program for five years and felt that the program gave students a chance to experience a degree of self-determination not found in the school's other classes. Two student teachers were teaching in science at the time the study was conducted.

The science teacher selected 30 students, 17 female and 13 male, from the eighth-grade classes to participate in the study. None of these students had previously received instruction on minerals and rocks. All had previously studied other units in the IS program and were familiar with the mechanics of the instructional materials. The measured IQs of the students participating in the study ranged from 91 to 133, with a mean of 105.

## Procedure

The study followed the pattern outlined below.

1. Administration of preinstructional concept structuring task probing for structural knowledge about minerals and rocks.

2. Administration of a three-part pretest on concepts in descriptive geology (described below).

3. Instruction using the ITE Minerals and Rocks.

4. Administration of posttest--same as pretest.

5. Administration of postinstructional concept structuring tasks--same as preinstructional.

The study was carried out over a period of six weeks, with one week for administering the concept structuring tasks both before and after four weeks of instruction. A three-part test was administered just prior to instruction as a pretest and again when instruction was completed as a posttest. The three sections of the pre- and posttests consisted of: (a) a multiple-choice test covering the science content of the ITE Minerals and Rocks, (b) a 17-item analogies test of key terms used in the instructional materials, (c) a 12-item set membership test in which each item contained a set of four terms, one of which the student had to identify as not belonging to the set. The pre- and posttests differed only in Section 1, which contained 45 item responses on the pretest and 16 additional responses on the posttest. These tests were administered by the classroom teacher.

The concept structuring tasks were administered in three parts. The first part probed students' knowledge structures of prerequisite science concepts, concepts the designers presumed students comprehended and that were necessary for comprehension of the science content in the ITE Minerals and Rocks. The second part probed structural knowledge of minerals, and the third part structural knowledge of rocks. For each task, a different set of cards on which the concepts were printed were used. The concept structuring tasks were individually administered, and each student was led through a practice task that consisted of cards containing familiar anatomical terms. The terms in the practice task, ATOM Task, MINERAL Task, and ROCK Task are listed in Figure 4 (page 12) under their respective headings. For both the practice task and each succeeding task, the student was shown the set of cards and asked if he or she recognized each term in the set. Then the student proceeded to arrange the recognized terms, as described previously in the discussion of the ConSAT. The arrangement was laid out on a large piece of paper (28 x 41 cm) and the cards, which had an adhesive on their reverse sides, were pressed into place. The procedure for administering the concept structuring tasks was the same before and after instruction.

## Results

Two types of analysis, one qualitative, the other quantitative, were applied to the data. Both analyzed the degree of correspondence between the knowledge structure representations generated by a student and a standard knowledge structure representation. The degree of correspondence between student and standard knowledge structure representations was determined by first identifying attributes that distinguish student knowledge structure representation from the standard knowledge structure representation and then assessing the extent to which these attributes are identifiable in the student knowledge structure representations. The qualitative analysis approach is described and illustrated in the following two subsections of this section.

Quantitative analysis transforms the raw concept structuring task data to a matrix representation. Matrices derived from student representations are compared with a standard structure derived from written materials.[4] Comparisons between student structures and this standard structure are made with respect to several different variables derived from the matrices. This quantitative analysis approach turned out to be inadequate for our purposes. However, the lessons we learned in the process were significant and, we feel, should be shared. For this reason, a description the technique and our "findings" are presented in Appendix A.

Qualitative Analysis of Concept Structuring Task Data

In the qualitative analysis, qualitative descriptions of the structural attributes of the standard structure were made. Student structure representations were searched for these attributes and then placed into categories based on the attributes.

---

[4]The content structures we used in these preliminary analyses have not been empirically verified in any way. The method for their derivation is made quite explicit so that the reader can make judgments about their validity.

The attributes and their qualitative descriptions derive from: (a) assumptions about the characteristics of structures produced by the subject-matter experts (or derived from their writings), and (b) hypotheses about how students with little or no knowledge about geology behave when confronted with a task composed of geologic terms. We have already discussed our assumptions about the relationships between content structure of instructional materials, structure of the discipline, and "expert" knowledge structures (see page 2).

Characteristics of any of the structures produced will be a reflection of the terms or words that comprise the task. Consider, for example, the words included in the ROCK Task (see Figure 4, page 12). The presence of the names of some specific rocks (granite, pumice, limestone, shale, slate, and marble) are likely to cue a facet of the subject-matter structure which represents classification. Of primary importance in the conceptual structure of physical geology is the way in which rocks and minerals are classified. Given an array of rock and mineral samples or their scientific names, a person knowledgeable in geology could select from a number of possible schemes for classifying the samples. However, given a structured stimulus (i.e., a concept structuring task) containing three key words (igneous, sedimentary, and metamorphic) that cue the classification of the rocks on the basis of the way in which they are formed, this structural characteristic is more likely to be elicited.[5]

Classification by this scheme using these words results in the hierarchical class-inclusion structure shown in Figure 5. This hierarchy represents words of three levels of abstraction. The words in

---

[5]A rock concept structuring task that replaced the terms "rock," "igneous," "metamorphic," and "sedimentary" with "crystalline structure," "chemical composition," "$CaCO_3$," and "hexagonal" would produce quite a different hierarchical classification based on a different conceptual scheme.

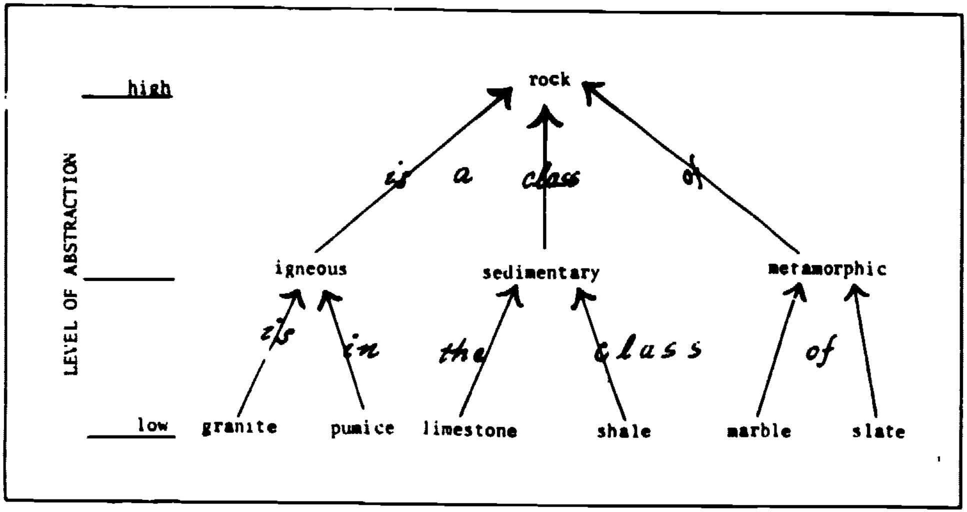



Figure 5. Hierarchical class-inclusion structure of 10 words in the ROCK Task.

the level of least abstraction are analogous and all bear the same relationship to words in the second level. Thus, each arrow in Figure 5 can be labeled in the same way, as shown by the underlined phrase in the following samples:

Granite _is in the class of_ igneous rocks.

Shale _is in the class of_ sedimentary rocks.

Slate _is in the class of_ metamorphic rocks.

The words in the second level of abstraction in Figure 5 are also analogous and all bear the same relationship to "rock." The relationship that holds between each of these words and "rock" is expressed by the underlined phrase in this example:

Igneous _is a class of_ rock.

Note that the relationship between words in the lowest level and the intermediate level and the relationship between words in the intermediate level and the highest level are _not_ the same.[6]

---

[6] Miller and Johnson-Laird (1976) discuss the hierarchical class-inclusion relationship as one in which the same relation holds between elements from one level to another. They call this the _IS A_ relationship.

Animal

Bird

Robin

While in everyday speech, the _IS A_ relation adequately expresses the relationship between robin and bird and bird and animal, in a scientific sense these relations are more exactly defined.

A Robin is a Bird

A Robin is a species of Bird

A Bird is an Animal

Birds (_Aves_) are a class of Animals

Included also in the words for the ROCK Task are "sediment," "magma," and "lava." These three words represent substances from which rock forms. These words do not fit into any hierarchical classification of rocks but can easily be incorporated into a structre that represents an important principle of geologic science--that any class of rock can be transformed into any other class of rock. This transformational process is cyclic and is called the rock cycle. We previously illustrated the rock cycle in one of the excerpts from the ITE Minerals and Rocks (see Figure 3, page 9), and it is shown more formally in Figure 6. In this figure, the arrows between the classes of rock do not always represent a single process. In fact, they often represent the stepwise occurrence of as many as five substeps. These substeps are detailed in Figure 7.

The complex set of transformations and relationships depicted in Figure 7 can be presented in a composite diagram of the rock cycle. An example of such a diagram is shown in Figure 8. Here the various transformations which apply to the particular rocks and other substances included in the ROCK Task[7] serve to illustrate and amplify the geologic principle embodied in the central representation of the rock cycle (cf. Figure 6). We might note that it was necessary to enter two rock names (limestone, shale) in two different places in the diagram of Figure 8 to make the composite representation complete.

Up to this point, the hierarchical class-inclusion relations of the words in the ROCK Task and their cyclical transformation relations have been considered separately. It should not come as a surprise, however, that the two kinds of structural relations of the ROCK

---

[7] The transformation of igneous rock to metamorphic rock was not greatly emphasized in the ITE Minerals and Rocks. However, all the other transformations were amply described.

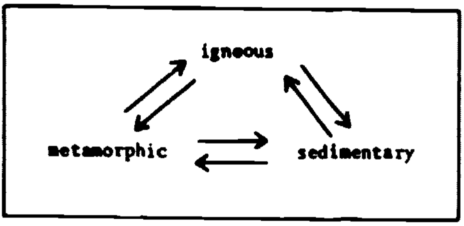
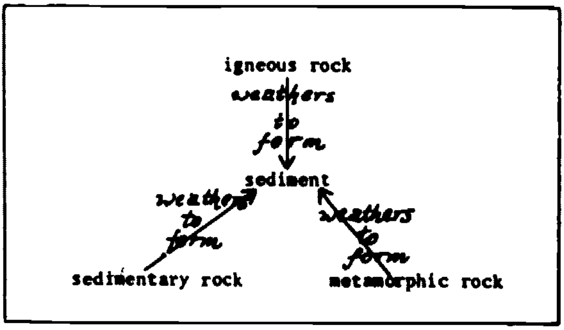



Figure 6. The rock cycle. (This structure simply represents the principle that any class of rock can be transformed into any other class.)

---

Formation of sediment by weathering.




Formation of magma when rocks are subjected to tremendous heat and pressure.

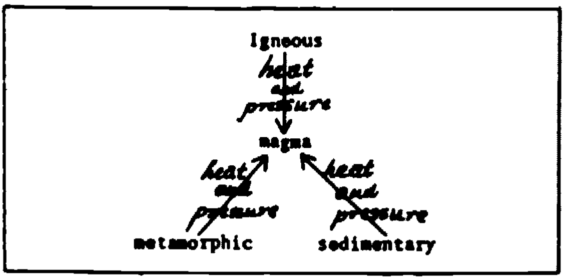



Figure 7. Substeps of the rock cycle transformations.

-continued-

The transformation of igneous and sedimentary rock to metamorphic rock by heat and pressure. (marble results when limestone is metamorphosed; slate results when shale is metamorphosed.)

igneous rock $\xrightarrow{\text{heat and pressure}}$ metamorphic rock

sedimentary rock $\xrightarrow{\text{heat and pressure}}$ metamorphic rock

sedimentary $\longrightarrow$ metamorphic

limestone $\longrightarrow$ marble

shale $\longrightarrow$ slate

Sedimentary rocks form when sediments are subjected to heat and pressure.

sediment $\xrightarrow[\text{pressure}]{\text{heat}}$ sedimentary rock

Igneous rock forms when lava and magma cool.

lava, magma $\xrightarrow{\text{cool}}$ igneous rock

Pumice is formed when lava cools rapidly (on the earth's surface).

lava $\xrightarrow[\text{rapidly}]{\text{cools}}$ pumice

Granite is formed when magma cools slowly (below the earth's surface).

magma $\xrightarrow[\text{slowly}]{\text{cools}}$ granite

Figure 7 (Continued)

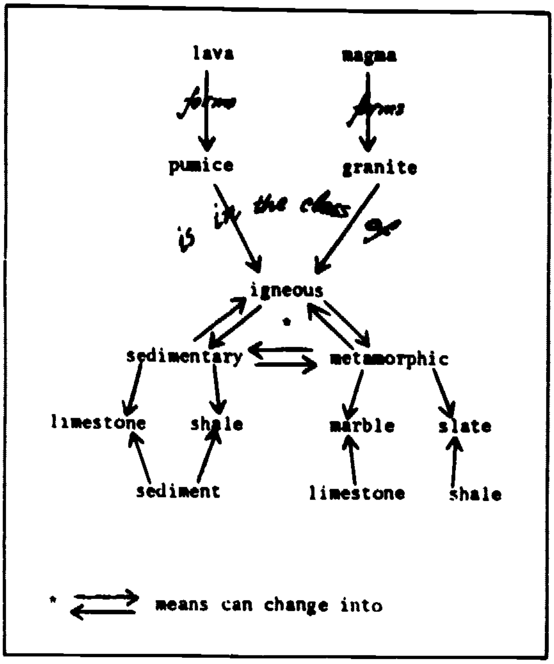



Figure 8. Composite representation of transformations and relationships in the rock cycle.

Task words can be integrated into a single structure. (In contrast, see the discussion of the MINERAL concept structuring task in Appendix B.) The integrated structure contains examples of rocks that can be incorporated both as members of the hierarchy and as examples of the rock cycle transformations. Diagrammatically, the integrated structure takes the form shown in Figure 9. Notice that this diagram is built around the hierarchical class-inclusion relations, but the structure could just as well have been visually displayed to highlight the cyclical transformation relations. This integrated structure (however displayed) represents our standard structure, one that an "expert" might produce.

An important feature of the integrated structure is its parsimony. There are other possible relations that might be added, but they add no meaning to the structure. For example, all of the examples of rocks could correctly be connected directly to "rock," but this information is already implied in the hierarchy. Similarly, "shale," and "limestone" could be connected this this way:

$$\text{shale} \xleftrightarrow[\text{sedimentary rocks}]{\text{are both examples of}} \text{limestone}$$

but again no meaning is added. The integrated structure shown in Figure 9 also is parsimonious in the sense that none of the ROCK Task terms are repeated, as was the case for the diagram in Figure 8. In a parsimonious way, the integrated structure represents the integration of two important facets of the structural basis of geology.

From our analysis of card-sort task data collected during the exploratory study previously mentioned (see page 7) and from the analysis of the science content structure, as exemplified in the preceding discussion, we have derived classes of structure for the ROCK

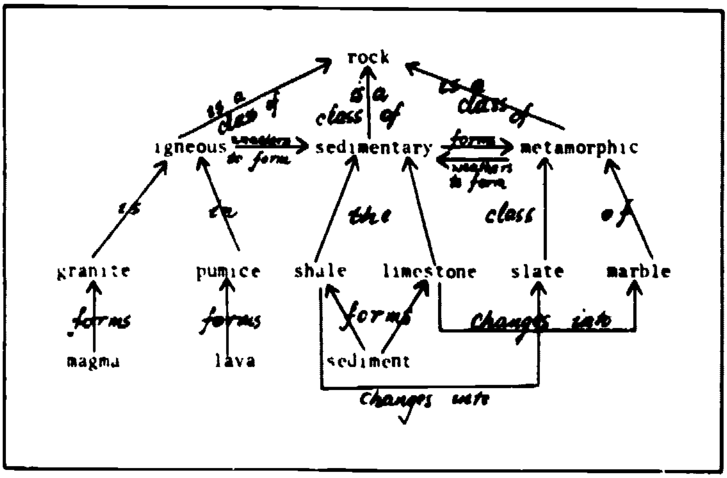



Figure 9. Integrated structure showing hierarchical and transformation relations of the 13 words in the ROCK Task.

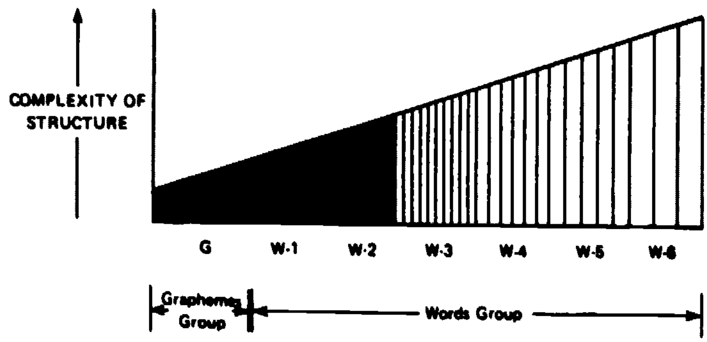
Task.[8] The diagram that appears in Figure 10 represents our initial conceptualization of seven classes of structures. The major division of the eight classes in the diagram into two groups (G and W) derives from the observation that a few of the youngest subjects in the exploratory study treated the geological words they were asked to group, not so much as words representing concepts, but more as graphemes. The schemes that they used to group or order the words could as well have been applied to groups of letters that are, in fact, not words.[9]

Within each of the two major groups (grapheme and word) of structures, the classes can be arranged in order of increasing complexity, as is displayed in the diagram in Figure 10. The increase in complexity is attributable to changes along one or more of several dimensions. Some dimensions have zero value (i.e., are not present) for "lower complexity" classes and only appear in "higher complexity" classes. Increasing values along a single dimension summed over dimensions contribute to the increasing complexity of structures within classes. Table 1 lists the six dimensions (or structural characteristics) that we have identified and some possible values along each dimension. To illustrate how these dimensions help to account for the complexity of a class of structures, in Table 2 we give the values along each dimension for structures falling in Class W.

---

[8] A structural analysis of the MINERAL Structure appears in Appendix B. This structure is considerably more complex than the ROCK Structure. It suggests more classes of structures and more attributes that describe salient features of the classes. We have elected not to incorporate the additional classes and attributes into our current analysis scheme.

[9] There are many other possible classes based on graphemes that we have not put in our diagram. For our present purposes, classes based on graphemes are not particularly important. We suggest, however, that this is an important group of structures. There are analogies based not on meanings of words but on their graphemological structure.




CLASSES OF STRUCTURES

| CLASS | ATTRIBUTES OF THE CLASS |
|---|---|
| W-6 | integration of hierarchical structure and transformational structure into a single structure |
| W-5 | hierarchical structure plus fragment of transformational structure |
| W-4 | hierarchical structure or transformational structure |
| W-3 | fragments of the hierarchical and/or transformational structures |
| W-2 | two or more words related by a single technical or general usage label |
| W 1 | two or more words, unspecified relationships |
| G | two or more words related by a single morphological characteristic |

Figure 10. Attributes and classes of ROCK Structures.

Table 1

Dimensions of Structural Complexity for Concept Structuring Tasks

| Dimension | Values (Categories) along the Dimensions |
|---|---|
| 1. Size of the unit which is structured | Single word<br>Pairs of words<br>Groups of words<br>Structure as a whole |
| 2. Relations between structural units are explicit | Unspecified relations (=0)<br>Relations are idiosyncratic<br>Relations represent common usage<br>Relations distinguish common usage and technical usage |
| 3. Relations between structural units are scientific | No discipline structure evident.<br>Some discipline structure evident<br>Represents discipline structure |
| 4. Degree of relationship among relations between units | Labeling (of 2 or more units with same term)<br>Networks--small and/or isolated<br>Interconnected networks<br>Fully organized |
| 5. Predictability of relations among structural units | None<br>Limited<br>Systematic |
| 6. Connections between concepts in structure | Few and mainly paired<br>Many and mainly paired<br>Many and nonpaired<br>Optimal and mainly nonpaired |

Table 2

Values of Each Structural Dimension for Class W-6

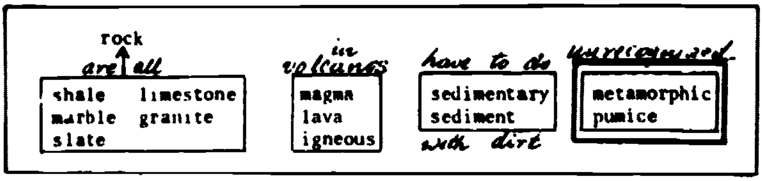
| Dimension | Value |
|---|---|
| 1. Size of unt which is structured. | Structured as a whole |
| 2. Relations between structural units are explicit | Distinguish common usage and technical usage |
| 3. Relations between structural units are scientific | Represents discipline structure |
| 4. Degree of relationship among relations between units | Fully organized |
| 5. Predictability among structural units | Systematic |
| 6. Connections between concepts in structure | Optimal and mainly nonpaired |

The values of dimensions of structures in other classes than W-6 will not be as definitive because of the overlap of categories. Nevertheless, the six identified dimensions appear to be useful in accounting for the structural complexity. They also were found to be useful in actually applying our analysis scheme to the data from the ROCK Task. Each set of data was analyzed independently by two coders. The reliability of our analysis scheme was determined by teaching the analysis scheme to an individual who, prior to instruction, was totally unfamiliar with the research. This individual also categorized the student structures. The interrater reliability was 70%, the two categorizers having agreed on 42 of 60 student structures. After consultation, the analysis scheme was revised slightly. This revision produced agreement between the coders on most of the structures where there had been differences. For the few remaining cases, where the revised analysis scheme did not produce agreement, the two coders reached a compromise in classification of the structures.

Illustrations of Qualitative Analyses

Pre- and postinstructional ROCK Structures produced by three students upon being given the ROCK concept structuring task were selected from the data to illustrate how the structures can be characterized using the analytical scheme presented in Figure 10. The examples chosen are representative of (a) levels in the analytical scheme, and (b) various degrees of pre- to postinstructional improvements. Our discussion in this section begins with lower levels on the scheme and smaller improvements and proceeds to higher levels and greater improvements. The three students' ROCK Structures are shown in Figures 11, 12, and 13. Each figure gives the student's identifying number and each structure is labeled pre- or postinstructional.

Preinstruction Structure




Postinstruction Structure

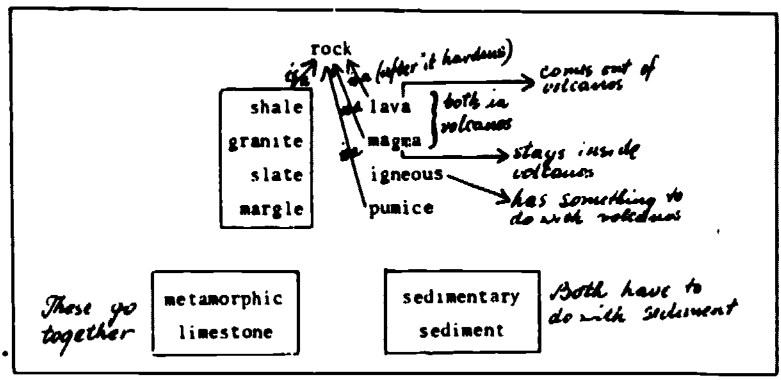


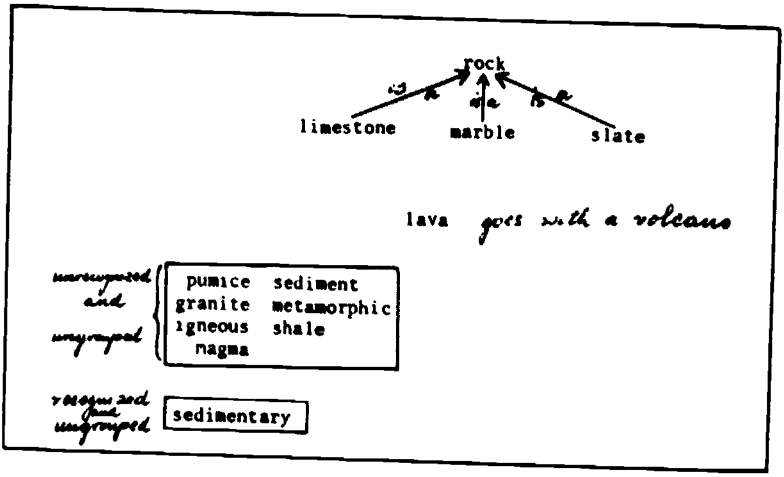

Figure 11. Pre- and postinstruction ROCK structures made by Student 3.

The pre- and postinstructional structures of Student 3 exemplify lower levels on the scheme and relatively minor pre to post changes. Student 3's structure before instruction is characterised by groupings on the basis of general (i.e., nonscientific) labels (rock, volcanoes, dirt). No evidence even of a fragment of the hierarchy is present. We assign this structure to class W-2. Student 3's postinstructional structure still has no sign of the hierarchical relations of rocks. More words are included under the general label, "rock"; the words organized around "volcano" are slightly more differentiated; "metamorphic" and "limestone" are paired, but no relation is given; and "sediment" and "sedimentary" are related by their morphological similarity. This structure has elements of classes W-2, W-1, and G (see Figure 10). The change, then, from pre- to postinstruction is minimal, with the student using essentially the same organizing relations, picking up little of the science content and none of the structure as outlined in the dimensions in Table 1.

Student 15's pre and post structures, presented in Figure 12, illustrate an improvement greater than that of Student 3's pre to post, as well as a structure at a higher level on our analytical scheme. Student 15's pre has many unrecognized terms, a few terms grouped under the general label "rock," and the association of "lava" with volcano. Student 15's post evidences a fragment of the hierarchy and an increase in the number of words associated with "rock" and with "volcano." The pre structure is characterized as Class W-2 in the scheme, and the post as Classes W-3 and W-2. There is a clear advance in structure, although there is still no well-defined hierarchy and no sign of the rock cycle.

Student 18's pre and post structures are representative of the highest levels of our scheme (see Figure 13). Although Student 18's structure does not contain the rock cycle, it is structured around the hieararchy. Note, however, that the hierarchy contains the words

Preinstruction Structure




Postinstruction Structure

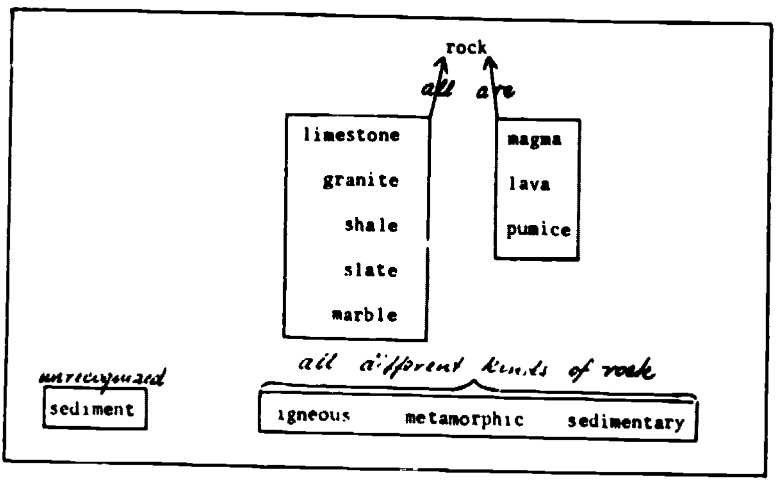
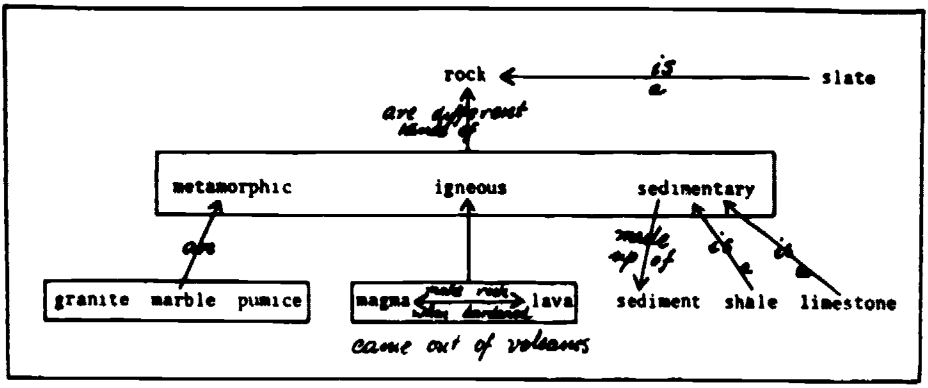



Figure 12. Pre- and postinstructional ROCK structures made by Student 15.

Preinstruction Structure




Postinstruction Structure

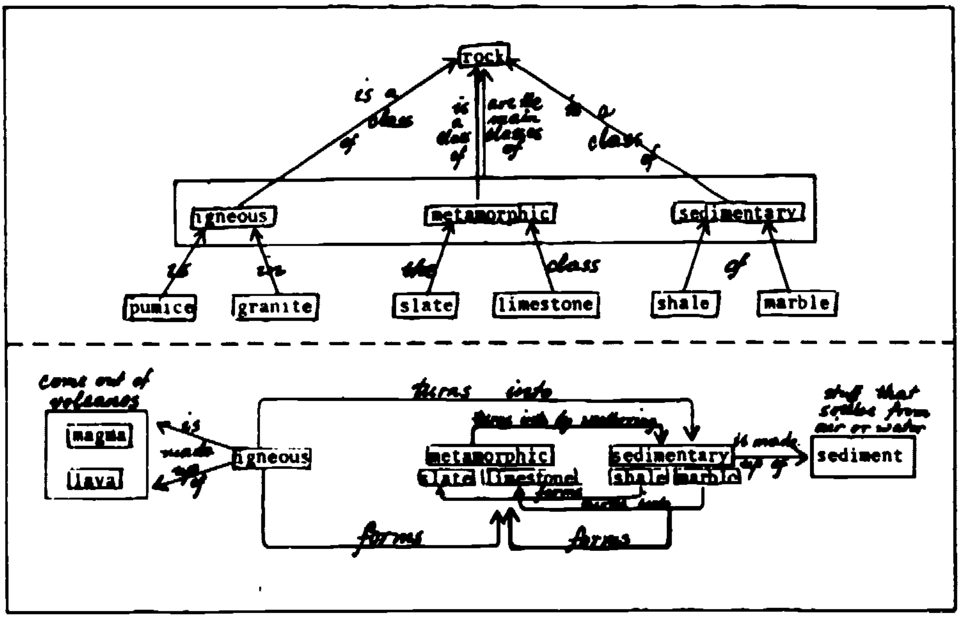



Figure 13. Pre- and postinstructional ROCK structures made by Student 18. (Note: The actual postinstruction structure had the hierarchy and the rock cycle integrated. They were separated to facilitate our analysis.)

"magna," "lava," and "sediment" on the same level as the examples of rocks. On way to view this is that the student tried to fit these words into one scheme, the hierarchy. However, in the post structure, these words are clearly related to rock cycle, and Student 18 incorporates the rock cycle structure and elaborates on the hierarchy. The rock cycle transformations are given both on the level of superordinate concepts ("igneous," "metamorphic," and "sedimentary") and on the basis of the examples of rocks. Student 18 demonstrates a clear and significant advance in structuring on the two tasks. The structure produced for the preinstructional class is characterized as Class W-3 and the post as Class W-6, an increase of three levels.

As stated, the structures of these three students are representative of the range of levels of structure as well as the kind of improvement from pre- to postinstruction. Student 15 (Figure 12) may be the example most like the "average" student: 19 of the 30 students improved one or more categories, and the mode shifted upward one category (from W-3 to W-4) from pre- to postinstructional tasks. Frequency distributions and degree of change in the ratings of the 30 students are found in Table 3.

Table 3

Frequency Distrubution and Degree of Change for ROCK Structuring Task (N=30)

| Score | $W_1$ | $W_2$ | $W_3$ | $W_4$ | $W_5$ | $W_6$ |
|---|---|---|---|---|---|---|
| Pre | 0 | 0 | 13 | 8 | 8 | 1 |
| Post | 0 | 0 | 3 | 12 | 6 | 9 |

Degree of Change (by number of categories)

| | |
|---|---|
| Up 3 | 1 |
| Up 2 | 4 |
| Up 1 | 14 |
| No change | 10 |
| Down 1 | 1 |

## Discussion

On the basis of our experience in the study described here, we are optimistic about the potential of the ConSAT as a means of probing, describing, and comparing science knowledge structures. Using this technique, we have been able to elicit representation of knowledge structures that include both the arrangement of concepts and the relationships on which the arrangement of the concepts is prediciated. We have devised an analysis scheme that allows us to define structural attributes of a specific concept structuring task (e.g., ROCK Structure) and have demonstrated that, on the basis of these attributes, knowledge structure representations elicited by a specific task can be categorized into meaningful groups. The attributes of the structures can be sufficiently well defined so that the analysis scheme can be easily taught to and reliably applied by an individual new to the analysis technique.

The part of the ConSAT for which there is the least theoretical or empirical validation is the process of defining the structural characteristics of a specific concept structuring task. This process, as it was carried out in the present study, relied almost exclusively on two individuals' interpretations of the science discipline structure relevant to the concepts for the relevant task. However, assuming that this process is adequate for the purpose of analysis, we can bring to bear the relevant science content structure on the definition of what constitutes a "good" representation via the task concepts of the cognitive structure in memory. The resulting classification of structures of increasing "goodness" contains structural classes that are rich in meaning, even though all of them are not easy to depict in a concise way.

Not only have we demonstrated that students' representations change as the result of instruction, but we are able to describe the specific characteristics of the structure that change. In most instances, the characteristic has a direct analog with the discipline structure of geology. For example, students classify specific kinds of rock as igneous, sedimentary, or metamorphic and show evidence that they recognize that this system of classification is based on a general principle of geology, namely that each class of rock can be transformed into either of the other classes.

From our analysis, we have been able to identify certain trends that have interesting implications for instruction. For example, we have some evidence that students whose preinstructional ConSAT tasks showed good structuring made greater gains in their ability to structure geological terms than those whose preinstructional ConSAT tasks showed no evidence of structuring of any kind. This observation seems to support the educational aphorism that the more you know, the more you learn. However, at issue here is the question of what it is that the more successful learner knows. Does the successful learner have a greater facility at storing discrete bits of information in a random fashion, or does he or she search the stimulus for organizing principles that permit the storage of many discrete bits of information in a single structure? With respect to this issue, we interviewed five students whose ConSAT tasks showed little or no structuring to determine the extent to which they used organizing principles when confronted with the task of classifying about 30 common foods. This task was overwhelmingly difficult for these five students. None were able to generate a scheme of classification that was applicable to all the foods. They could only classify foods with which they or members of their immediate family had had experience. This suggests that these students are unaware of structuring as a strategy for reducing large amounts of information into more manageable units. It is not surprising that these students are unable to structure geological terms which are both unfamiliar and highly abstract.

Our ConSAT, an extension of the card-sort method for probing and representing knowledge structures used by Shavelson (1974) in his study of three methods for representing structures, differs in several important ways from his method. While these differences add considerable complexity to the quantitative analysis of the data and subsequent representations of knowledge structures as Shavelson does them (see Appendix A: Quantitative Analysis), the complexities are more than compensated for by the richness of the knowledge structure representations and subtle differences in representations that can be detected by the qualitative analytical procedures we apply to the representations. Although conciseness is a definite characteristic of the numerical values that depict particular variables resulting from a quantitative analysis of the data and also has the potential advantage of making possible rather rigorous statistical comparisons of structures between groups or between individuals, the conciseness and rigor are more than offset, we believe, by what is lost in the translation.

Our preliminary attempts to extend the use of the ConSAT indicate that the technique has broad general applicability with respect to science content and can be used successfully with subjects as young as 8 years old. Our interest in the ConSAT, however, reaches beyond its use as a tool of research. Helping students develop an awareness of structuring strategies for science content is an important instructional goal and challenge of our work. We expect to carry out this instructional design work, which has been informed by our research, as we continue to pursue further research.

## References


Champagne, A. B., & Klopfer, L. E. An individualized elementary-school science program. Theory into Practice, 1974, 13, 136-148.

Ford, G. W., & Pugno, L. (Eds.). The structure of knowledge and the curriculum. Chicago: Rand McNally, 1964.

Harary, F., Norman, R. Z., & Cartwright, D. Structural models: An introduction to the theory of directed graphs. New York: John Wiley, 1965.

Johnson, P. E. Associative meaning of concepts in physics. Journal of Educational Psychology, 1964, 55, 84-88.

Miller, G. A., & Johnson-Laird, P. N. Language and perception. Cambridge, Mass.: Belknap Press, 1976.

Ore, O. Theory of graphs. Providence, R. I.: American Mathematical Society Colloquium Publs., 1962, 38.

Preece, P. F. W. A note on the comparison of cognitive structure and subject-matter structure. Journal of Research in Science Teaching, 1976, 13, 353-354.

Schwab, J. (Ed.). Education and the structure of knowledge. Chicago: Rand McNally, 1964.

Shavelson, R. J. Some aspects of the correspondence between content structure and cognitive structure in physics instruction. Journal of Educational Psychology, 1972, 63, 225-234.

Shavelson, R. J. Methods for examining representations of a subject-matter structure in a student's memory. Journal of Research in Science Teaching, 1974, 11(3), 231-249.

Shavelson, R. J., & Stanton, G. C. Construct validation: Methodology and application to three measures of cognitive structure. Journal of Educational Measurement, 1975, 12, 67-85.

# APPENDICES

## APPENDIX A

### Quantitative Analysis of Concept Structure Task

In addition to the qualitiative analysis of the students' structures, we are attempting to develop a useful quantitative method for making comparisons between structures. Since we assume that the structures are a representation, at least approximately, of the way in which concepts are structured in a student's memory, it may be said that we are developing a quantitative method for comparing cognitive structures.

The mathematical model underlying the method we use is derived from the theory of directed graphs.[10] In applying our method, we transform the arrangement of the words in a structure into a simplified digraph, which shows only the connections between words. One such digraph is obtained from a knowledge structure representation based on inferences about the discipline structure of geology.

This digraph is designated as the standard structure. Additional digraphs are derived from each structure made by a student, and each of these digraphs represents a student's response structure. The next step in our method is to measure the degree of similarity between the student's response structure and the standard structure.[11] We do this by calculating the values of certain sc lar variables from a deviation matrix showing the absolute difference between the sum of the first and second stage communication matrices of the standard and student's

[10] Relevant discussions of the theory of graphs may be found in Ore (1962) and Harary, Norman, and Cartwright (1965).

[11] Shavelson (1972) adopted a similar strategy in his comparison of cognitive structures and a content structure in physics. However, as Preece (1976) pointed out, the results Shavelson obtained may have been an artifact of the transformation he used in manipulating the entries in his matrices, a difficulty we avoid in our method of analyses.

response structures. The general procedure for calculating the deviating matrix, D, is displayed in Figure A-1.

In order to utilize this general procedure for the ROCK concept structuring task, it was first necessary to derive a standard structure for the words included in this task. This was done and the standard structure digraph for the ROCK tasks is displayed in Figure A-2. Using the procedure outlined in Figure A-1, a sum matrix was calculated for the standard structure, and this matrix also is displayed in Figure A-2. The sum matrix for the standard structure was used to calculate the deviation matrix, D, for each student response structure derived from a task.

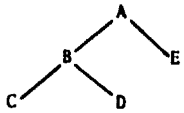
From the data collected, we derived pre- and postresponse structure digraphs and the corresponding deviation matrices for each student for the ROCK task. By way of illustration, Figure A-3 shows six response structures for the ROCK task and their corresponding deviation matrices. These particular student response structures and matrices were derived from the same pre- and postinstructional ROCK tasks illustrated in the qualitative section (see Figure 11).

To evaluate a student's response structure (i.e., to measure the degree of similarity between the response structure and the standard structure), numerical values for a number of scalar variables may be calculated from the deviation matrix D. Of seven such variables we constructed, we will describe one, the product of the column vector ($X_1$) and the row vector ($X_2$) of the D matrix. This scalar variable ($X_1 X_2$) is nonmetric, and its computational formula is:

$$X_1X_2 = \sum_{i=1}^{n}\left[\left(\sum_{k=1}^{n} d_{ki}\right)\left(\sum_{k=1}^{n} d_{ik}\right)\right]$$

where $X_1$ = column vector of the sum of the row elements of the D matrix, and $X_2$ = row vector of the sum of the column elements of the D matrix.

Given the standard structure for the task words:




Calculate the one-stage communication matrix C, where each (i, j) entry indicates a non-directed connection between two elements of the structure.

$$C = \begin{vmatrix} 01001 \\ 10110 \\ 01000 \\ 01000 \\ 10000 \end{vmatrix}$$

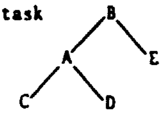
Calculate the two-stage communication matrix $C^2$. [In this matrix, $c^2_{ij}$ $(i \neq j)$ is the number of directed paths in the structure that go from $x_i$ to $x_j$ in two steps, and $c^2_{ij}$ $(i = j)$ is the number of one stage connections for the given element in the structure.]

$$C^2 = \begin{vmatrix} 20110 \\ 03001 \\ 10110 \\ 10110 \\ 01001 \end{vmatrix}$$

Calculate the sum matrix $M = C + C^2$.

$$M_1 = \begin{vmatrix} 21111 \\ 13111 \\ 11110 \\ 11110 \\ 11001 \end{vmatrix}$$

Given the student's response structure of the structuring task words:




By the same procedure as above, calculate the sum matrix for the student's response structure.

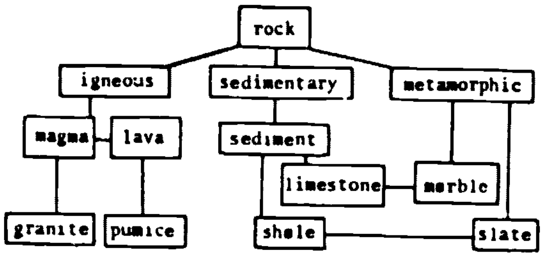
$$M_2 = \begin{vmatrix} 3111 \\ 12111 \\ 11110 \\ 11110 \\ 11001 \end{vmatrix}$$

Calculate the absolute difference between the sum matrices of the student's response structure and the standard structure:

$$\text{Deviation matrix } D = \left| M_1 - M_2 \right| = \begin{vmatrix} 10000 \\ 01000 \\ 00000 \\ 00000 \\ 00000 \end{vmatrix}$$

**Figure A-1. Procedure for calculating the deviation matrix.**

ROCK Structure

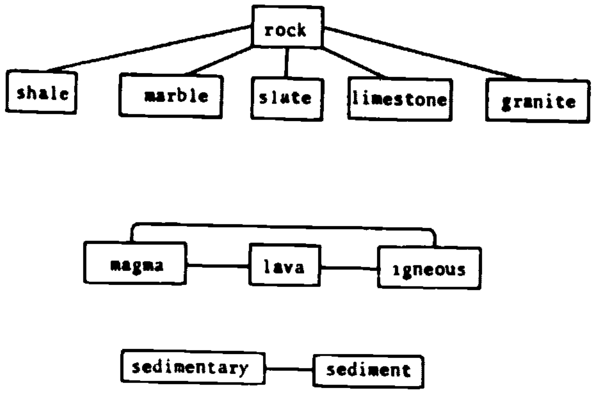



$M_1$ =

| | rock | igneous | sedimentary | metamorphic | limestone | lava | magma | sediment | marble | granite | pumice | shale | slate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rock | 3 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| igneous | 1 | 2 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| sedimentary | 1 | 1 | 2 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| metamorphic | 1 | 1 | 1 | 3 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| limestone | 0 | 0 | 1 | 1 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| lava | 0 | 1 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| magma | 1 | 1 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 1 | 1 | 0 | 0 |
| sediment | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 3 | 1 | 0 | 0 | 1 | 1 |
| marble | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 1 |
| granite | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| pumice | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| shale | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 1 |
| slate | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 2 |

**Figure A-2. Standard structure and corresponding sum matrix for ROCK Task.**

**3 Pre**



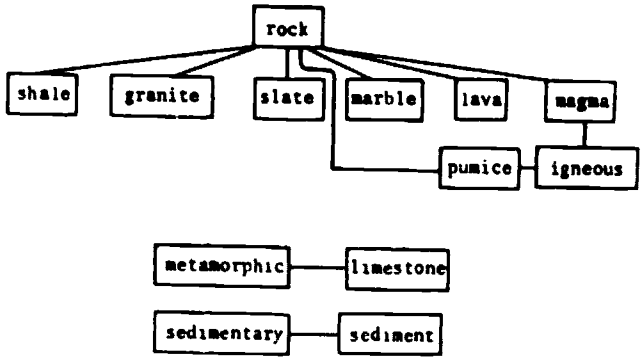

D =

| | rock | igneous | sedimentary | metamorphic | limestone | lava | magma | sediment | marble | granite | pumice | shale | slate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rock | 2 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 |
| igneous | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| sedimentary | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| metamorphic | 1 | 1 | 1 | 3 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| limestone | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |
| lava | 0 | 1 | 0 | 0 | 0 | [illegible] | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| magma | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| sediment | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 1 |
| marble | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
| granite | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 1 |
| pumice | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| shale | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |
| slate | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 1 |

**Figure A-3. Pre- and postinstructional response structures for three students and corresponding deviation matrices.**

**-Continued-**

**3 Post**

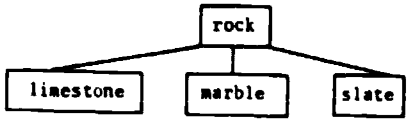



D =

| | rock | igneous | sedimentary | metamorphic | limestone | lava | magma | sediment | marble | granite | pumice | shale | slate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rock | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| igneous | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| sedimentary | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| metamorphic | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| limestone | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| lava | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| magma | 1 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 1 | 0 | 0 | 0 |
| sediment | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 1 | 1 |
| marble | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| granite | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 1 | 1 |
| pumice | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| shale | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |
| slate | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 0 |

**Figure A-3 (Continued)**

15 Pre

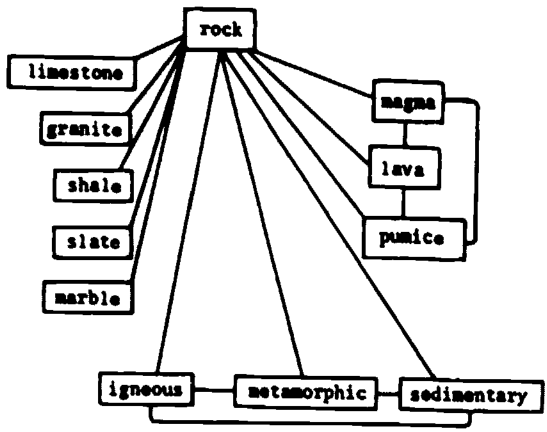



D =

| | rock | igneous | sedimentary | metamorphic | limestone | lava | magma | sediment | marble | granite | pumice | shale | slate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rock | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 |
| igneous | 1 | 2 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| sedimentary | 1 | 1 | 2 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 |
| metamorphic | 1 | 1 | 1 | 3 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 |
| limestone | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |
| lava | 0 | 1 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| magma | 1 | 1 | 0 | 0 | 0 | 1 | 3 | 0 | 0 | 1 | 1 | 0 | 0 |
| sediment | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 3 | 0 | 0 | 0 | 1 | 1 |
| marble | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| granite | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 |
| pumice | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 |
| shale | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 1 |
| slate | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 |

**Figure A-3 (Continued)**

**15 Post**

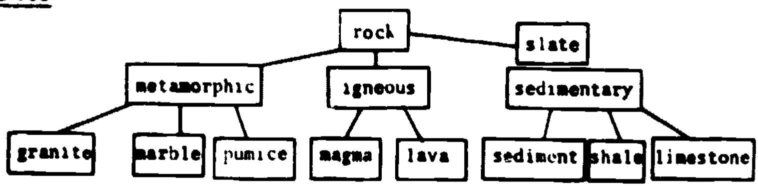



D =

| | rock | igneous | sedimentary | metamorphic | limestone | lava | magma | sediment | marble | granite | pumice | shale | slate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rock | 8 | 2 | 2 | 2 | 1 | 3 | 2 | 1 | 0 | 1 | 3 | 1 | 0 |
| igneous | 2 | 1 | 2 | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| sedimentary | 2 | 2 | 1 | 2 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| metamorphic | 2 | 2 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| limestone | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |
| lava | 3 | 0 | 1 | 1 | 1 | 1 | 2 | 0 | 1 | 0 | 2 | 1 | 1 |
| magma | 2 | 0 | 1 | 1 | 1 | 2 | 0 | 0 | 1 | 0 | 2 | 1 | 1 |
| sediment | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 3 | 0 | 0 | 0 | 1 | 1 |
| marble | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 |
| granite | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| pumice | 3 | 1 | 1 | 1 | 1 | 2 | 2 | 0 | 1 | 1 | 2 | 1 | 1 |
| shale | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| slate | 0 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 1 |

Figure A-3 (Continued)

**18 Pre**

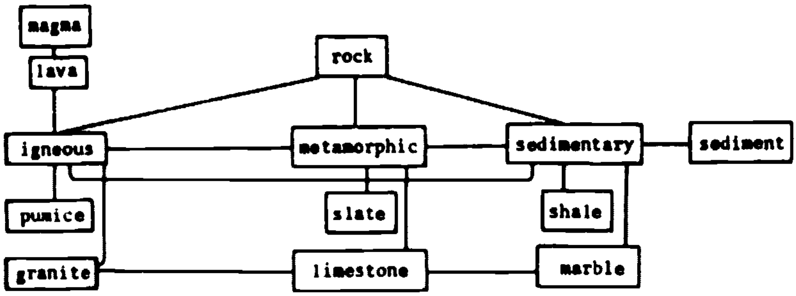



D =

| | rock | igneous | sedimentary | metamorphic | limestone | lava | magma | sediment | marble | granite | pumice | shale | slate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rock | 1 | 0 | 0 | 0 | 1 | 1 | [illegible] | 0 | 0 | 1 | 1 | 1 | 0 |
| igneous | [illegible] | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| sedimentary | [illegible] | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| metamorphic | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| limestone | [illegible] | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| lava | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| magma | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 1 | 1 | 0 | 0 |
| sediment | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 |
| marble | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |
| granite | 1 | 1 | 0 | 1 | [illegible] | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 |
| pumice | [illegible] | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
| shale | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| slate | [illegible] | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |

**Figure A-3 (Continued)**

1B Post




D =

| | rock | igneous | sedimentary | metamorphic | limestone | lava | magma | sediment | marble | granite | pumice | shale | slate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| rock | 0 | 2 | 2 | 2 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| igneous | 2 | 5 | 2 | 2 | 2 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 |
| sedimentary | 2 | 2 | 4 | 2 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 2 |
| metamorphic | 2 | 2 | 2 | 2 | 0 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 0 |
| limestone | 1 | 2 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 0 | 1 | 1 |
| lava | 1 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| magma | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| sediment | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 1 |
| marble | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| granite | 1 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 |
| pumice | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| shale | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| slate | 0 | 1 | 2 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 |

**Figure A-3 (Continued)**

With respect to evaluating a student's response structure, the $X_1X_2$ variable can be interpreted as the sum of the number of incorrect connections leading away from a word in the structure multiplied by the number of incorrect connections leading to that same word <u>plus</u> this sum for every other word in the structure. For a given student's response structure, the interpretation of that numerical value of $X_1X_2$ is that this response structure lies at a certain distance from the standard structure. The larger the numerical value of $X_1X_2$ is, the further away is the student's response structure from the standard structure. To illustrate, the numerical values of $X_1X_2$ for the six response structures displayed in Figure A-3 are shown in the first variables column of Table A. The numerical values of the $X_1X_2$ variable increase geometrically with increasing deviations of a student response structure from the standard structure.

Table A

Illustrative Numerical Values for the $X_1X_2$ Variable
Used to Evaluate Student Response Structures
for the ROCK Concepts Structuring Task

| | Variable |
|---|---|
| Student Response Structure | $X_1X_1$ |
| 3 Pre | 572 |
| 3 Post | 355 |
| 15 Pre | 580 |
| 15 Post | 2180 |
| 18 Pre | 314 |
| 18 Post | 1153 |

The qualitative analysis ignores a considerable portion of the information contained in the raw data. For our purposes, this loss in information is not adequately compensated for by the advantages of quantification. A major problem with this method of analysis is that it yields results that correspond poorly with the results from the qualitative analysis. One source of this poor correspondence is the extent to which the numerical values derived from the qualitative analysis are influenced by the presence in student structures of connections that do not appear in the standard structure. The presence of one such connection can result in a numeral rating of a structure that places the structure in the poor range of scores, when in fact the structure has many more of the structural attributes of the standard structure than another student structure that has a higher numerical score.

We are continuing to study the quantitative analysis in an attempt to make it a more valid method of analysis.

## APPENDIX B

### MINERAL Concept Structuring Task

The MINERAL concept structuring task does not "fall out" so neatly as does the ROCK task, where two major sets of relations can be combined to form a single integrated structure.

Given the words and phrases of the MINERAL task (see Figure 4), the definition of a mineral provides a major structure (see A of Figure B-1). Mineral class membership and nonmembership relations form a second structure (see B of Figure B-1). The hierarchical relations that exist between a specific kind of rock, the minerals of which the rock is composed, and the chemical composition of the minerals expressed both as a chemical name (e.g., Calcium Carbonate) and formula (e.g., $CaCO_3$) define a third structure (see Figure B-2).[12]

The structure in Figure B-3 is a representation reflecting the chemical relationships among the words as contrasted with the geological relationships represented in Figure B-2. Note particularly that from a chemical perspective, calcite, limestone, and seashells are roughly analogous, while geologically they are quite distinct. Figure B-4 depicts graphically how the chemical properties of several substances are compared with the properties that define the characteristics of minerals to determine whether or not the substance in question is a mineral.

---

[12] This structure is designated "hierarchical," but it should be noted that it is composed of two different relations. Limestone <u>physically</u> contains calcite crystals. Calcite "contains" calcium carbonate in the sense that upon chemical analysis, the mineral, calcite, will be found to consist of calcium carbonate, which is presumed to mean molecules of calcium carbonate.

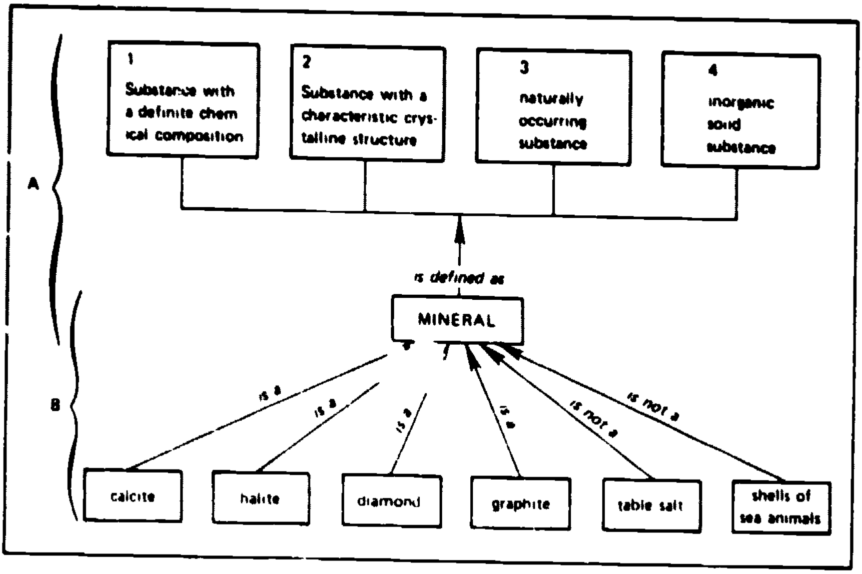



Figure B-1. Mineral definition (A) and mineral class membership and nonmembership (B) structures.

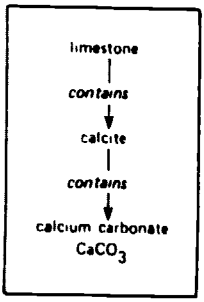
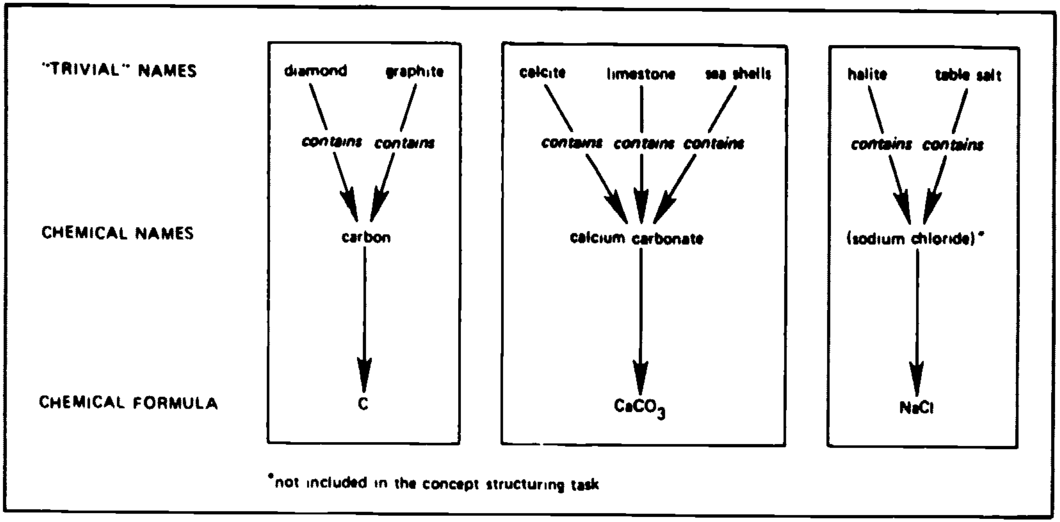



Figure B-2. Rock composition structure.




B-3. Chemical relations structure.

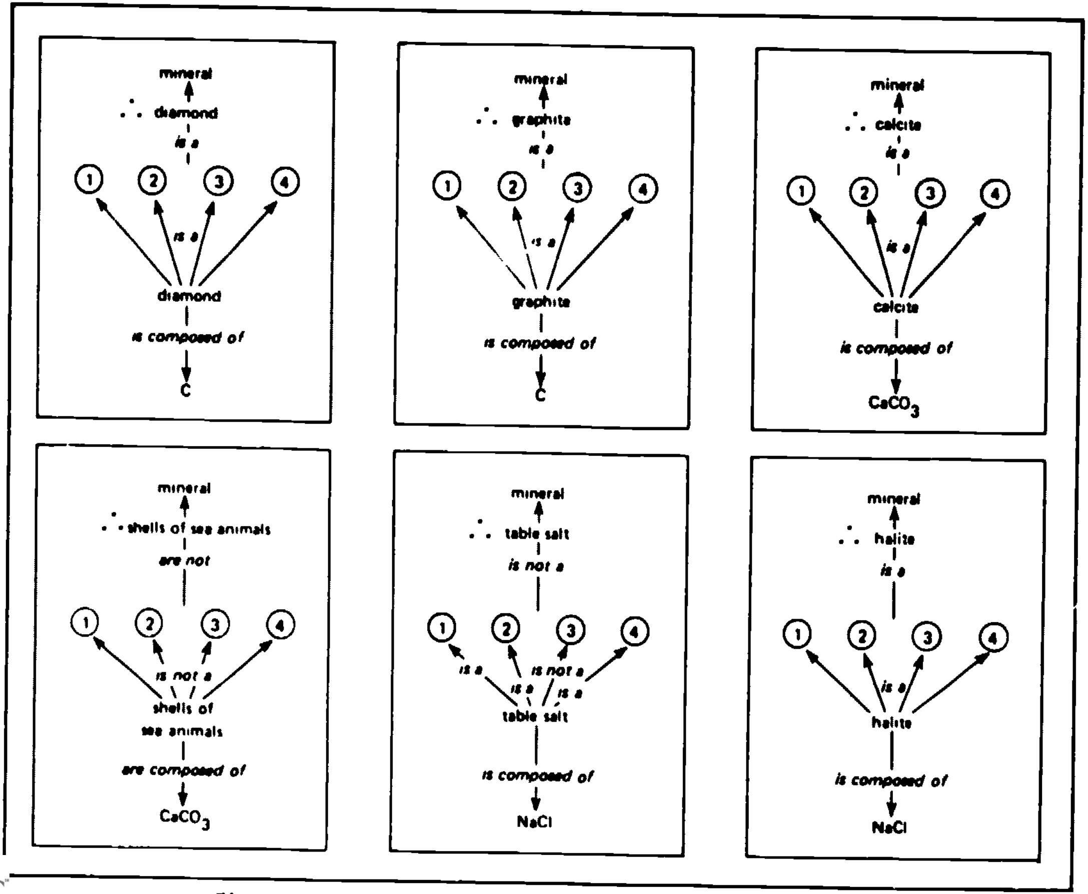



Figure B-4. Origins of chemical and geological distinctions.

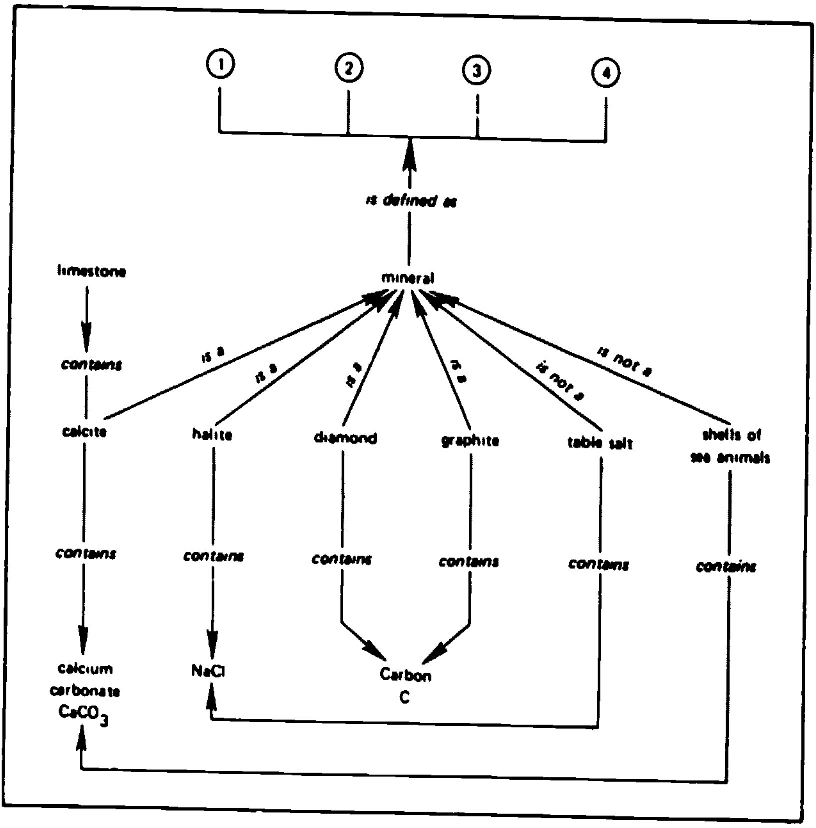



Figure B-5. Integrated structure.

The integration of these structures is somewhat easier to perform "in the head" than on paper and, as we have done it (Figure B-5), many of the subtleties are no longer evident.