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ABSTRACT

The author attempts to show the development of logical-empirical knowledge structures from the raw elements in nature to the structures of knowledge as perceived by the mature student. Eighteen hypotheses are identified which focus on the expected relative natures of perceived knowledge structures of the various agental groups and their relationship to the types of curricula used. These hypotheses are used to provide a context within which to view relevant research. In this review the definition of "psychological structure of knowledge" accepts in principle the underlying theoretical positions of Ausubel and Dyer. A schema is presented illustrating the flow of knowledge structures as they encounter various transformations and interpretations from the raw unstructured events of the environment enroute to those of the mature student, and attention is drawn to the distinction between the processes involved in structuring the various science curricula. A 104-item bibliography is included with the paper. (Author/PEB)

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Psychological Structures of Knowledge in Science Education

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Abstract

This paper attempts to show the development of logical-empirical knowledge structures from the raw elements in nature to the structures of knowledge as perceived by the mature student. A survey of science as a knowledge-structuring enterprise, psychological theory relevant to knowledge structures, and contemporary high school science curricula, together with a model of flow of structure from one curricular agental group to another, suggest several hypotheses concerning psychological knowledge structures. These hypotheses, extracted from the literature, provide a context within which to view the relevant research.

In this review the definition of "psychological structures of knowledge" accepts in principle the underlying theoretical positions of Ausubel and Dyer. The recent emergence and growing emphasis of this structure concept in education appears to reflect extant psychological research, the advent of the electronic media, the structure and nature of science and the entry of scientists into the arena of curriculum writing.

Kuhn indicates that the knowledge-structuring enterprise of science only progresses as scientists work within paradigmic constraints; without the paradigm structures of knowledge are essentially non-existent. The education learning theories of Ausubel, Gagné, and Bruner all empha-

the importance of establishing meaningful psychological knowledge structures, particularly for purposes of transfer. The NSF supported science curricula, the unified and the integrated science curricula emphasize the "big ideas" of science as opposed to presentations of surveys and numerous disjoint facts in traditional curricula.

A schema is presented illustrating the flow of knowledge structures as they encounter various transformations and interpretations from the raw unstructured events of the environment enroute to those of the mature student. Attention is drawn to the distinction between the processes involved in structuring the various science curricula.

Eighteen hypotheses are identified which focus on the expected relative natures of perceived knowledge structures of the various agental groups, and their relationship to the types of curricula used. Only a few of these are given attention in the research literature. The methodology employed in measuring comparative perceptions of knowledge structures is being refined and several interesting results may be noted. A change in perceived structure is observable as the student becomes more familiar with the subject material; newly learned material becomes anchored in existing knowledge structures; a convergence of student perceived knowledge structure toward content structure is observable; comparative psychological knowledge structures of curricular agental groups tend to agree with the schema and relevant hypotheses identified in this review.

This form of research is still in its infancy; little attempt is made to anchor it in theory. This paper may provide the basis for moving in that direction.

*This author wishes to express his appreciation to Drs. Fischler, Hughes, Segal, and Simco for their guidance in preparing this review.

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> Grasping the structure of a subject is understanding it in a way that permits many other things to be related to it meaningfully. To learn structure, in short, is to learn how things are related (Bruner, 1960, p. 7).

The concept of the structure of knowledge is not new. It has been a topic of much discussion and concern, either for purposes of philosophic refinement, for clarifying one's view of reality or for curriculum development and refinement by men like Plato, Aristotle, Descartes, Kant, Vico and Comte among others. In our present century Bruner generally is given credit for alerting educators to the importance of considering structures of knowledge in curriculum development (Foshay, 1970; Kliebard, 1965; Bellack, 1966; Robinson, 1968). A flurry of articles written by philosophers of science and educational psychologists has resulted. It has, in a measure, awakened the opposing views of the structuralists and the unified science defendents to new verbal combat. Despite the claim of Kliebard (1965) that "structure of the disciplines" has already become a slogan to the educationists and academicians, the structural approach has demonstrated its function in the development of such curricula as Physical Science Study Committee (PSSC), Chemical Education Material Study (CHEM Study), and Biological Sciences Curriculum Study (BSCS) and the various unified and integrated science curricula. Within the past decade researchers have begun to focus on students' perceptions of knowledge structures in science.

It is the psychological structures of knowledge in science, as exhibited by the mature student, that forms the principle focus of this paper. The "mature" student is one intellectually performing at (in Piaget's parlance) the formal operational level, and chiefly concerns the high school student. An overview of the organization of this paper will now be presented.

Overview

After the relevant terms have been clarified and defined, brief consideration will be given to the possible reasons for the recent emergence of the structure emphasis. Following this, a rationale will be presented for surveying three major areas: science as a knowledge structuring enterprise, educational psychological theories that emphasize psychological structures of knowledge, and general structural features of contemporary high school science curricula. Having established this theoretical basis, hypotheses will be identified which concern psychological knowledge structures in science. These hypotheses will provide a focus in studying the research literature in the area. The analysis will be restricted to those studies which attempt directly to identify and analyze perceptions of knowledge structures in science.

DEFINITION of TERMS

Several undefined or variously defined terms referring to the structure of knowledge are used in the literature. This section will seek to clarify their definition.

Basic Definitions

Structure

The word "structure" connotes order and organization as opposed to random disarray. Randomness by its very nature escapes elaboration while structure is subject to an analysis of organization. Ford and Pugno (1964), using the structure of a molecule as an example, state that structure "refers to the parts of an object and the ways in which they are related (p.2)". Morrissett (1967), using examples from economics, elaborates

> Structure is the arrangement and interrelationship of parts within a whole. A structure can refer to the relationship of concepts to each other; for example, the concepts "economic system" and "political system". Conversely, a concept may itself have a structure. The concept "economic system" can also be thought of as structure, having component concepts such as "money" and "spending" which are structurally related to each other (p.4).

Structure suggests relationships that are meaningful or potentially meaningful. This is implied in Ausubel's (1964) elaboration of the distinction between logical and psychological structures of knowledge.

Structure of Science

"Structure of science" has reference to the total evolutionary, intelligent, nonrandom process of theory generation, theory-data matching, and theory revision; this includes an interwebbing of product and process. Novak (1965) views it as "the system of major generalizations or concepts together with the process by which these concepts are obtained and enlarged (p.72)". To do justice to a meaningful definition of "structure of science" requires expanded elaboration as attempted by Nagel (1961), Kuhn (1962), and Robinson (1968), to name but a few.

Structure of the Disciplines

Schwab (1964) views the concept of the "structure of the disciplines" as involving three basic problems. The first relates to the organization of the disciplines; for example, is the knowledge obtained from mathematics significantly different than that obtained from chemistry or physics? Or does the distinction between living organisms and nonliving organizations of matter demand different conceptual frames and different methods for their investigation? The second problem concerns the substantive structure of each discipline; what is the conceptual structure that is guiding the research of the discipline? The third problem concerns the manner and method of knowledge verification; it involves what Schwab (1964) calls the syntactical structures of the disciplines. Each of these three problems have a bearing on organization of knowledge for curricular purposes and will be referred to again later in this paper.

Although "structure of knowledge" may have a broader connotation for many authors, Knotts (1971) maintains "The phrase, structure of knowledge, implies structure of knowledge in a discipline (p.28)".

Structure of a Subject

In his initial reference to structure in The Process of Education, Bruner (1960) uses the phrase "structure of a subject". This has been generally interpreted as "structure of a discipline" (Foshay, 1970; Kliebard, 1965). What may, or may not be regarded as an acceptable discipline, however, is debatable. Kliebard (1965) indicates that Bruner does not suggest "that any field of study must present an approved pedigree in order to be admitted to membership as a discipline (p.600)". Bruner elaborates on his view of "structure of a subject" by referring to observations in nature and extracting from the data relationships that help to explain new phenomena. An understanding of commutation, association and distribution in algebra provides a structure that helps to solve numerous new, though related, problems. In another example, referring to the syntax of a sentence he clarifies his definition by stating "Having grasped the subtle structure of a sentence, the child very rapidly learns to generate many other sentences based on this model though different in content from the original sentence learned (p.8)". In all his examples, Bruner implies "structure of a subject" to be an organized interrelationship of entities which are functional for identifying new relationships in the disciplines.

Cognitive Structure

An alternative term for "psychological structures of knowledge" is "cognitive structure". Ausubel (1963) defines cognitive structure as "an individual's organization, stability and clarity of knowledge in a particular subject matter field at any given time (p.26)". Dyer expands on Ausubel's definition. Cognitive structure

> is an individual's organization of knowledge in a certain subject matter area at a given time, where organization refers to the relationships between cognitive elements (p.18).

She elaborates on the elements and the relationships thus - the elements

> might mean what is usually termed a concept, a principle, an event, a fact, an object, a theory, or a substructure, which could be larger or smaller than a theory. The type of element in a structure depends upon the particular subject matter area (p.4) . . . . Relationships are the connections between elements in a body of knowledge (p.6).

These include: descriptive, causation, multiple causation, temporal logical, quantitative, functional and composite (an interaction of any of the preceding).

Content Structure

Dyer's (1969) definition of "content structure of knowledge" is similar to that of "cognitive structure" and is analogous to Ausubel's formal or logical structure of knowledge. She defines it as "the organization of a given area of knowledge where organization refers to the relationships between the elements within that area (p.4)". Elements and relationships are defined as previously for cognitive structures of knowledge.

Expanded Definitions

Ausubel and Taylor have expanded their theoretical definitions of knowledge, pointing out theoretical distinctions or categorizations.

Distinction Between Logical and Psychological Structures of Knowledge

Ausubel (1966) makes a distinction between logical and psychological structures of knowledge with respect to four of their principle attributes. While phenomenological meaning is an idiosyncratic psychological experience, logical structure can at best have potential meaning.

> Subject-matter material possesses logical or potential meaning if it consists of possible and nonarbitrary relationships that are relatable on a nonarbitrary, substantive basis to a hypothetical human cognitive structure exhibiting, in general, the necessary ideational background and cognitive maturity (Ausubel, 1966, p.223).

Secondly, although psychological organization of knowledge is governed by the laws of meaningful learning and retention and logical organization of knowledge concern the logic of classification, there is some overlap. The major difference between the two organizational processes is the fact that the psychological structure of knowledge is subject to decrement throughout its development and that the learning of new ideas and their resistance to the decrement are a function of the existence and nature of subsumers. Thirdly, the two structures differ with respect to the sequential placement, ordering and general organization of the component elements. A fourth distinction between the logical and the psychological structures of knowledge depends upon the cognitive maturity of the content. The psychological structure of knowledge of a developing child at the concrete operational level will differ from that of a high school student. Furthermore, the psychological structure of knowledge of the high school student will tend to be much less sophisticated than that of a mature scientist-philosopher.

Distinction Between Empirical and Logical Structures of Knowledge

Taylor (1966) makes a distinction between empirical and logical structures of knowledge. While logical structures refer primarily to abstract hypothetic-deductive systems, empirical knowledge structures refer to the facts, concepts and principles which constitute the subject matter of a discipline. These are similar to Schwab's substantive structures of the discipline.

Author's Definitions

For the sake of this review the author will use a definition of psychological structures of knowledge in science which accepts in principle the underlying theoretical positions of Ausubel and Dyer. Furthermore, "structure of knowledge" will have a relative connotation only; the specific meaning will depend upon the context in which it is used. The term "empirical-logical" knowledge structures will refer to the composite knowledge structures generated by a science discipline.

RATIONALE

Recent Emergence of the Concept of Structure

The recent emphasis on structure appears to have arisen, in part, as a result of and/or coincident with the existing paradigm given emphasis in psychological research. Bruner (1960) indicates that the trend of research in psychology at the turn of this century was away from emphasis on general understanding to one of specific skill acquisition. It was not until about two decades ago that American psychologists redirected their research to problems concerned with the type of complex learning that one finds in the school environment. Educational psychologists such as Ausubel and Gagné have been concerned with learning as it occurs in the classroom. They have generated paradigms related to knowledge structures which have met with some success in such complex learning situations.

Marshall McLuhan (1963) presents a rather interesting sequence of events for what may have initiated the 'sudden acceptance of the "structural" approach in all fields today'. The structural approach involves depth awareness of a simultaneous field of relations.

> This in turn supposes dialogue, rather than description, in teaching and learning, and insight in place of a mere point of view. The structural approach substitutes team for specialism, and pursues causes and effects, in all situations, rather than aiming at a visual chart of data and organization. The structural approach is not an affair of "views" nor single planes nor analytic <u>isolation of</u>

functions (McLuhan, 1963,p.57-58).

(Underlined word italicized in original). Non literate societies depended primarily on the ear for sensing and perceiving their environment. A measure of the structural was represented in such closely knit societies in the free flow of dialogue that encouraged expression of a diversity of views. Literate Western man replaced the ear with the eye; information now flowed in a lineal fashion through his eye-gate. "In obtaining an eye for an ear, Western man clearly abandoned depth or structural knowledge in favor of applied knowledge (p.62)". The discovery of electromagnetic waves, however, again provided the means for dialogue, thus providing the basis for a return to structure.

> That the discovery of electromagnetic waves was a "prodigious biological event" indicates the moment of shift from the lineal and mechanical form to the "structural" awareness which fills the horizon of Professor Bruner. It is important to observe that the quality of the new "structural", as opposed to the old lineal, sequential and mechanical, is the quality of the simultaneous (McLuhan, 1963,p.63)

Perhaps what gave the greatest impetus to an emphasis of the structural approach is the nature and structure of science itself. Concern for the relevancy of structure existed in the minds of the creators of the new NSF supported science curricula. Bruner (1960) states

> The scientists constructing curricula in physics and mathematics have been highly mindful of the problems of teaching the structure of their subjects, and it may be that their early successes have been due to this em-

> phasis. Their emphasis upon structure stimulated students of the learning process (p.8).

It was the scientists in the various disciplines who played the major roles in constructing the new high school curricula in the three major sciences. The structure, and the degree of emphasis of structure, observed in these curricula very much reflects the structure of the disciplines.

Interrelationships Between Logical and Psychological Knowledge Structures.

Some thirteen years have passed since Bruner admitted to the "early successes" of the new curricula. Perhaps the curricula's global effectiveness today is more seriously questioned in view of the level of difficulty and abstraction they generally emphasize (Brauer, 1963; Cohen, 197_). Be that as it may, one cannot deny that the positive sciences, physics and chemistry, have demonstrated great success in expanding man's horizons into the unknown. And it is the very procedures of structuring knowledge, that the scientists corporately employ, that have enabled them to make such phenomenal progress (Kuhn, 1962).

The organized body of knowledge generated by the scientific community is exemplified in their theories, principles, and laws as recorded in their journals and discussed in conferences (Kuhn 1962). The organizing procedures involved in structuring this knowledge (both empirical and logical) are a reflection of the psychological knowledge structuring activities of the individual scientist. In discussing the distinctions between the processes of organizing the logical and the psychological structures of knowledge, Ausubel (1966) indicates how the laws of logical classification are similar to those of meaningful learning and retention.

> Nevertheless these two sets of process laws overlap to the extent that the meaningful learning of new ideas conforms to principles of logical classification insofar as it may be described as a process of subsumption under those relevant existing ideas in cognitive structure which exhibit a higher order of generality and inclusiveness. Thus not only do both kinds of organizational processes rely on the logic of classification, but they also employ the same principle of structuring knowledge in terms of unifying elements which manifest the greatest generality, inclusiveness, and explanatory power, and which are capable of relating and integrating the widest possible array of subject matter (p.224-225).

The empirical-logical structures of knowledge, as generated by the scientific community, provide the substantive resources, either directly or indirectly, for structuring the science curricula. Due to their degree of sophistication, the structures must first pass through the hands of the interpreters, the curriculum writers. Here they are normally refined, shorn of their abstraction (yet retaining a strong emphasis of the structure of science) and adapted to match the cognitive functioning of the student. Perhaps this is stating the ideal, for one may question the true flavor of science in traditional curricula, or one may question whether sufficient consideration of the students' intellectual maturity has been given in some of the NSF supported curricula.

The psychological knowledge structuring processes of the mature student are fundamentally similar to that of the scientist. (This by virtue of the fact that both are classified as intellectually performing at the formal operational level according to Piaget). However, while the scientist works with the unstructured elements of the environment, the student obtains direction, and concepts to be assimilated from a prepared curriculum. The nature of the psychological structures of knowledge of the student (ie. his perceptions of the nature of the organization of a given subject matter) should therefore largely reflect the organizational structure of the curriculum.

The curriculum will, however, not be the sole determinant of the student's psychological structures of knowledge. His structures will be additionally a function of both the degree of interaction of the teacher in the learning situation and of the teacher's perceptions of the structure of the given body of knowledge. Thus both the psychological knowledge structures of the teacher and the structure of knowledge of the curriculum are immediate factors in shaping the psychological structures of knowledge of the student.

The preceding paragraphs indicate that a network of interplay exists among the raw unstructured events of the environment, the psychological structures of knowledge of the scientist, the empirical-logical knowledge structures generated by the scientific community, the knowledge structure of the curriculum, and the psychological structures of knowledge of the teacher and of the student. Further elaboration of knowledge structuring in science, of theories of psychological knowledge structuring and of applications of structuring in the curricula should elucidate these issues.

KNOWLEDGE STRUCTURES - PROCESSES,

THEORIES and APPLICATIONS

Science - A Knowledge-Structuring Enterprise

In his book, The Structure of Scientific Revolutions, Kuhn (1962) attempts to capture the structure of science within a sociological context. The concept of what he calls a "paradigm" lies at the heart of his exposition and supplies unity and meaning to his treatise. Paradigms are defined as "universally recognized scientific achievements that for a time provide model problems and solutions to a community of practioners (p. viii)". In further elaboration of his definition he states that they are characterized by sufficiently unprecedented achievements to "attract an enduring group of adherents away from competing modes of scientific activity" and they are "sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to solve (p.10)".

There have been times, however, when paradigms have been non existent. There were no model problems and solutions to guide the scientists. There were no communities of scientists to mutually solve common problems using accepted methodology. Such periods are characterized by random experimentation generally lacking rationale. Under such circumstances little progress is made. There is no meaningful building on previous research. Each scientist is essentially working at the grassroots level.

During this "route to normal science" much disconnected data is generated not only because each scientist is dabbling randomly but also because no particular methodology has been established as to what leads to acceptable or non-acceptable data.

> In the absence of a paradigm or some candidate for a paradigm, all of the facts that could possibly pertain to the development of a science are likely to seem equally relevant. ...Furthermore, in the absence of a reason for seeking some particular form of more recondite information, early fact-gathering is usually restricted to the wealth of data that lie ready to hand. The resulting pool of facts contains those accessible to casual observation and experiment together with some of the more esoteric data retrievable from established crafts like medicine, calendar making, and metallurgy (p.15).

During this pre-paradigmic period structure of knowledge is essentially non-existent, though perhaps not completely so at the primitive, specific level. No discipline exists. There is little commonality and unity of purpose between those experimenting. There is little meaningful communication between these individuals. Kuhn traces the pre-paradigmic activities carried out with light and electricity before acceptable paradigms emerged. Both are characterized by initial random questing, by the generation of multiply competing paradigms, and by the eventual adoption of a paradigm that stabilizes, provides direction and lends progress to the research enterprise. He indicates that this is the normal birth procedure of any science both historically and the development of new sciences in our present day.

Historically, one can perhaps recognize a correlation between the state of development of the sciences preceding Galileo and Bacon with the then accepted role and nature of philosophy. King and Brownell (1966) state

> Until nearly the twentieth century, Western philosophy generally preceded in thought and dominated all other disciplines of knowledge through four relations; ... (1) it provided the unity for all knowledge, (2) although clearly under attack by the sixteenth century it provided knowledge of reality, (3) it posed and answered epistemological questions about knowledge and knowing, and (4) it directed scientific knowledge toward new goals and open new paths (p.40,41).

The empiricists, who regarded empirical science, and not mathematics, as the ideal form of knowledge were frequently influenced by the rationalist philosophical systems, systems which regard reason as an independent source of knowledge of the physical world (Reichenbach, 1968). The purely rationalist philosophy was simply not compatible with a burgeoning, blooming knowledge-structuring enterprise in the natural sciences.

The acceptance of a paradigm completely transforms the activities of the practitioners and provides the basis for emergence of a discipline, for the generation of structures of knowledge. The paradigm proves to be the "guiding star" for meaningful, non-random investigations. Kuhn (1962) states

> No natural history can be interpreted in the absence of at least some implicit body of intertwined theoretical and methodological belief that permits selection of facts - in which case more than "mere facts" are at hand - it must

> be externally supplied, perhaps by a current metaphysic, by another science, or by personal and historical accident (p.16,17).

Basic to its functioning is the question of going from the facts to a concept or theory. (Whether or not "beauty exists in the eye of the beholder" suggests a multitude of questions in perception as well as in philosophy. Hanson (1969) has elucidated this question within a scientific context in his book Patterns of Discovery).

Frank (1957) elaborates on the question of induction as considered by Mill and Whewell. Although Mill's position was one of concepts existing external to the mind, Frank points out that the position of Whewell is the presently accepted view.

> Whewell, however stressed the point that the "concepts" that lead to new inductions are not forced upon us by the observed facts, but are built up by an activity of our minds which constructs these new conceptual schemes, using as building material the linquistic material that has either existed within our minds for a time or has been built up just for the purpose of securing an adequate system of concepts (p.305).

As support for this view Kuhn (1962)further elaborates

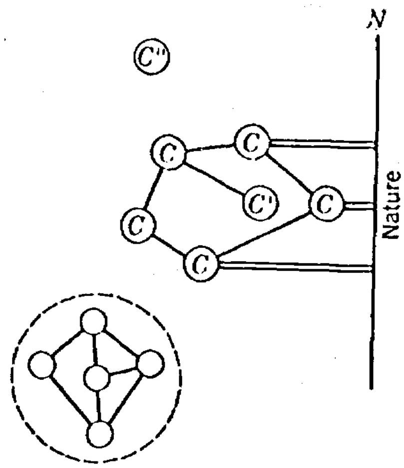
> No wonder, then, that in the early stages of any science different men confronting the same range of phenomena but not usually all the same particular phenomena, describe and interpret them in different ways (p.17).

The existing structure of knowledge provides the frame of reference from which to view the vast ocean of the unknown, it provides the foundation upon which to build further research; and..

as a foundation it must be firmly anchored, well organized, stable and clear.

The structuring of scientific knowledge employs the invention and usage of constructs - a construction of the human mind which helps the scientist to understand and interpret the world about him (Margenau, 1950). These constructs must have some connection, either directly or indirectly, with the objective world, and may cluster to form a theory. Margenau (1950) lists six metaphysical principles that determine the choice of acceptable constructs: they must be logically fertile, or manipulable; they must be characterized by multiple connections either to other constructs through formal definitions or to observables in nature through epistemic definitions; they must be permanent and stable, that is for the lifetime of the theory; they must be extensible, helping to explain phenomena previously thought to be unrelated; they must be capable of generating causal laws; and they must be characterized by simplicity and elegance. Numerous similarities can be noted between the above requirements and our definition of the structure of knowledge.

Margenau (1950) represents a model of scientific constructs and their inter-connectedness within a theory in a schema. The circles, representing constructs, must connect to the real world, either directly or indirectly, via epistemic



definitions, in order to qualify in an acceptable knowledge structure in science. The constructs, and the connections between constructs, must be logically sharp and clear. Constructs not so connected are not within the purview of scientific investigation.

These constructs thus assist the scientist in structuring the knowledge obtained within the constraints of the existing paradigm. Where the discipline has moved beyond the descriptive, beyond the correlational stages, as is the case with the positive sciences, logical hypothetic-deductive theoretical systems are generated. These logical structures of knowledge represent the epitomy of scientific erudition and intellectual elegance. Logical deductions from these inductive systems provide ideas for research, which in turn provide the feedback concerning the acceptability of the theory.

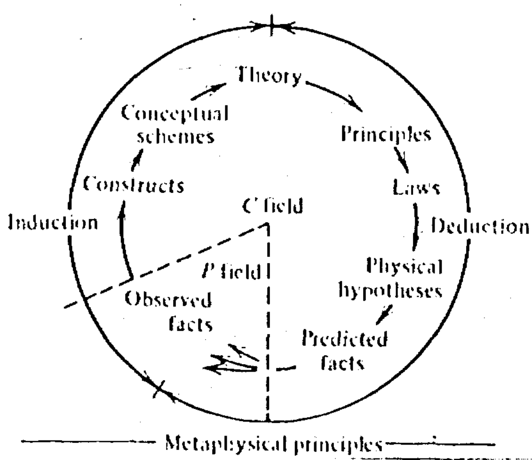
The theories or empirical-logical knowledge structures, however, require continual articulation, verification and refinement. Margenau (1950) indicates that it is necessary to connect a theory with sufficiently dissimilar sets of observable events, within acceptable error variance, in the real world in order to establish it as a "varifact".

Questions of organization, stability and clarity in building up knowledge structures are of extreme importance, as the graduate student very well knows, in the painful agonizing exercises he encounters in literature searches and in establishing acceptable rationale in research proposals. Poorly anchored research is anathema to the scientific community. The quality of cohesiveness, organization, stability and clarity of the knowledge structure is a function of the existing paradigm constraints and the critical review by the scientific community.

Historically, as the scientific community penetrated deeper into the verification and articulation of their paradigms and theories, their dependence upon philosophy withered (King and Brownell, 1966). Frank (1957) indicates that technology was responsible for severing science from philosophy. As a result of this schism the differences between the disciplines became more distinct, thus establishing distinct structures of knowledge.

During the "normal science" period, or what Schwab (1964) calls the "static science" period, the activities of the scientists are of a first order nature; their concern is to obtain data to fit the theory, to compare empirical observations with the "box" they've constructed. Both Kuhn (1962) and Schwab (1964) elaborate on a second order activity where the concern of the scientist is to find a better theory, a better fitting "box". Schwab calls this fluid science; Kuhn regards this period as a scientific revolution. When a new paradigm has been found, which Kuhn says is initiated by the anomaly, a complete restructuring of theory results. The structures of knowledge must always be regarded as tentative at any one time; over an extended period they are in a dynamic state of continual change, not in a simply additive fashion, but in an eruptive fashion demanding at times complete re-organization (Kuhn, 1962).

Robinson (1968), in summarizing some of the writings of several authors of philosophy of science, expresses the scientific enterprise in the model below.



The eventual emergence of a paradigm (thus culminating that specific scientific revolution) causes the scientist to see the world in a new way. It is somewhat analogous to a gestalt switch. Kuhn (1962) says that after the scientist's perceptions have been re-educated, "the world of his research will seem, here and there, incommensurable with the one he had inhabited before (p.112)". Now that he has a new view of the world, old data takes on a completely different meaning. Kuhn (1962) provides an example from the history of science.

> The very ease and rapidity with which astronomers saw new things when looking at old objects with old instruments may make us wish to say that, after Copernicus, astronomers lived in a different world. In any case, their research responded as though that were the case (p.117).

No doubt the effects of such transformations of perception eventually filter down to the general public and transform their "Weltanschauung".

One might generalize the "box-fitting" activity of the scientist with the expression $F(N) \longleftrightarrow G(C)$ where $F(N)$ represents some generalized function of the matrix of all elements in nature, that is the observables, and $G(C)$ represents some generalized function of the matrix of all cognitive elements, essentially psychological structures of knowledge, represented in the scientific community. $F(N)$ is continually changing as new areas are tapped, due both to stumbling on new phenomena and phenomena created by cognitive processes, and as scientists approach the limits of accuracy in measurement. $G(C)$ is continually changing since the process of theory adoption, articulation and rejection is dynamic. The symbol "$\longleftrightarrow$" suggests that as time progresses $G(C)$ more accurately maps into $F(N)$.

Summary

In summary, the following statements may be made about the knowledge structuring aspect of science:

1. If no paradigm exists, then there is no identifiable structure of knowledge.
2. Where there is no identifiable structure of knowledge, there is no organismic scientific community or discipline.
3. Adoption of a paradigm by a group of people provides both the direction for questing and the necessary constraints for meaningful knowledge structuring. All new information generated from research must be firmly anchored in existing structures and provide a meaningful solid basis for future knowledge structuring.
4. Constructs, meeting the requirements set by the scientific community, are invented to help man understand natural phenomena. These are meaningfully connected to each other, to form theories; and they are joined, either directly or indirectly, to the real world for purposes of verification.
5. The state of a knowledge structure must be regarded as the product of a human enterprise and is therefore tentative and dynamic.

Psychological Structures of Knowledge and Psychological Theory

Several educational psychologists have developed theories pertaining to knowledge structure and knowledge structure acquisition within the school context. Although the major concern here is with the knowledge structures per se, these do have implications for issues in pedagogy. Both will be presented briefly.

Ausubel's Subsumption Theory

The principle of subsumtion forms the basis of Ausubel's theory of meaningful verbal reception learning. The subsumer is essentially a psychological knowledge structure in a given area reflecting the past learning of the individual and providing the necessary anchorage for future learning. It is hierarchical in nature with the more inclusive concepts at the apex and the more specific concepts and facts subsumed under such abstractions. (Its role in learning is analogous to that of schema in Piaget's developmental theories). If meaningful learning is to occur, the subsumer must be well organized, stable and clear. It must be sufficiently abstract to subsume new learning material encountered.

For meaningful learning to occur suitable subsumers must exist in the cognitive structure of the individual; there must be some formal resemblance between the new material and some subsumer. If such structures are available,

> subsumption of the traces of the learning task by an established ideational system provides anchorage for the new material, and thus constitutes the most orderly efficient, and stable way of retaining it for future availability (Ausubel, 1964,p.230).

The newly subsumed material is initially readily dissociable from the subsumer (and the degree of dissociability is a function of overlearning or the number of practice trials of the learner) but as time progresses it is completely "captured" by the subsuming system (obliterative subsumption). This process extracts and retains those elements of the material representing its least common denominator (or the "invariants" in Gibson's terms, 1967), thus providing for greater cognitive economy and more efficient manipulation. "Thus the same subsumability that is necessary for meaningful reception learning somewhat paradoxically provides the basis for later forgetting (Ausubel, 1964, p.230)".

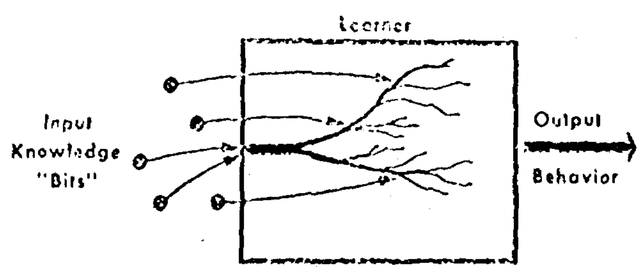
Ausubel differentiates between derivative and correlative subsumption. Derivative subsumtion occurs when the learning material constitutes an illustration of a previously learned general proposition, or is a specific example of an established concept in cognitive structure. Such materials are quickly obliterated, but also readily "reified" by appropriate cognitive manipulation induced by new exposure to similar materials. Correlative subsumption, however, occurs when the learning material is essentially new, perhaps an extension of materials learned earlier, and is subsumed by that structure that is most similar to the new material. Because of the formal difference between the entities, the new subsumed material is not retrievable and is therefore forgotten.

The concept of transfer in this theory is somewhat different than that in the laboratory. In experimental studies it usually refers to discrete tasks, whereas here it refers to a continuum. Ausubel emphasizes the importance of stable, clear, well organized structures in problems of transfer.

> Since potentially meaningful material is always learned in relation to an existing background of relevant concepts, principles, and information, which provide a framework for its reception ... it is evident that stability, clarity and organizational properties of this background crucially affect both the accuracy and the clarity of these emerging new meanings and their immediate and long-term retrievability (Ausubel, 1964, p.234).

Rote learning occurs when the new materials learned are non-relatable to any subsumer in cognitive structure. No anchors exist to capture the material; it is readily forgotten.

Novak, Ring and Timar (1971) have captured Ausubel's subsumption model in a schema.



Schema showing that additional meaningful learning can result in subsumption of prior concepts into larger, more inclusive concepts.

Ausubel's theory has pedagogical implications. The teacher must start where the child is at. If the child's existing subsumers, relevant to the intended learning task, lack clarity, stability or organization, measures should be taken to remedy the situation before moving on to new materials. If relevant subsumers are non-existent, advance organizers, (abstractions of the materials to be presented) should be presented and anchored to existing structures with appropriate familiar materials. Materials should always be presented in hierarchical fashion, from the general abstractions and overviews to the details. The details should be continually intercompared with other materials so as to enhance clarity of structure.

Gagne's Hierarchical Theory

While Ausubel's theory is concerned with reception learning, Gagné's theory, as presented in Conditions of Learning (1965), is primarily concerned with the acquisition of intellectual skills. Thus, although Gagné does not minimize the relevance of cognitive structures, his focus is primarily on pedagogical implications of his theory.

Gagné lists eight types of learning generally representing the hierarchical order of skill acquisition from the simple to the abstract. These include: signal learning, stimulus response connections, motor chain learning, verbal associate learning, discriminations, concept learning, rule learning and problem solving. With perhaps the exception of motor chain and verbal associate learning the higher abstract performances cannot be carried out without first mastering the simpler ones.

> Although the learning of defined concepts and rules may well represent some

> frequent goals of a formal schooling process, it would be mistaken to believe that these goals can be reached by simply ignoring all other forms of learning or by pushing the latter into a kind of trash can of unimportant events. The varieties of learning described here are possible only because they have been preceded by the acquisition of a set of prerequisite capabilities that extends down to the simplest stimulus-response connection (Gagne, 1965,p.189).

Gagné identifies two types of transfer of learning. Lateral transfer occurs when skills are successfully applied to new, though inherently similar, conditions. Vertical transfer occurs when acquisition of a distinctly new skill is achieved because of mastery of simpler intellectual skills.

A meaningful structure of intellectual skills is essential for learning to occur. Speaking of reinstatement of intellectual skills from memory, Gagné (1965) states that learning involving symbolic activities seems to be "strongly affected by a hierarchical ordering that makes one skill dependent on the prior learning of another skill that has a lower location in the hierarchy (p.83)". Furthermore, in referring to meaningful verbal, non-rote, learning "Individuals learn and retain inclusive categories, generalizations, and summarizing propositions, which in turn aid their learning and remembering of specific facts (p.153)". Even the verbatim learning of verbal chains appears to be markedly affected by the presence of organizing principles.

The theory summarized here provides meaningful suggestions to the educator wishing to teach intellectual skills. After the teacher has identified the terminal behavior desired, one needs to ask "what skills need to be mastered before the final objective can be met?" Each of the subsidiary skills are further broken down to the level of present performance of the child. This hierarchical scheme now provides a meaningful guide in ordering the intermediate materials so as to obtain the terminal objective.

Bruner's Theory

In his summary and reflections of the Woodshole Conference in The Process of Education, Bruner (1960) states the advantages that accrue from structuring the curriculum along disciplinary lines. He maintains that the results of such efforts will make a subject more comprehensible, will enhance memory of detail organized in structured patterns, will provide for transfer of training both specifically and generally and will aid in narrowing the gap between "advanced" and "elementary" knowledge.

In another volume, Toward a Theory of Instruction, Bruner (1966) discusses the elements that should characterize a good theory of instruction. Such a theory must specify the experiences which most effectively implant in the student a predisposition to explore alternatives within a problem situation. This involves the controlling of uncertainties, knowing when to relinquish guidance, and mastering the problem of suitably defining goals for the individual student.

A theory of instruction should further specify the procedures of structuring knowledge for optimum economy and power, economy in the memory of detailed relevant relationships and power that is fruitful for generating solutions to new problems. The procedures may entail the ikonic, enactive or symbolic forms of representation. Since their mastery occurs hierarchically during cognitive development, their order should generally be respected in presenting new materials. Sequencing, however, must always be considered in view of the needs of the individual. In emphasizing the need to be cognizant of structure, Bruner states that not much is known on how to teach structure effectively but maintains that the best minds in the disciplines can make a great contribution in this area.

The theory must furthermore provide guidelines in forming and pacing reinforcement. When and how to provide informative feedback, "knowledge of results", is a determinant of the students' continuing performance.

Bruner (1961) is a strong advocate of discovery learning. Allowing a student to arrive at a concept independently will help him to be a constructionist, to organize his knowledge so as to account for observed regularities and to provide a basis for further findings. Bruner posits that the degree to which one tends to carry out learning activities with the autonomy of self-reward is directly proportional to the degree that one is able to approach learning activities with the task of discovering something rather than "learning about" it. Furthermore,

> it is only through the exercise of problem-solving and the effort of discovery that one learns the working heuristics of discovery, and the more one has practice, the more likely is one to generalize what one has

> learned into a style of problem solving or inquiry that serves for any kind of task one may encounter - or almost any kind of task (Bruner, 1961,p.31).

And finally, discovery learning should aid the student in retention as the associations he forms are uniquely his.

Summary

All three theorists attach considerable importance to the existence of knowledge structures particularly for purposes of transferring successfully to new problem situations. Ausubel is more explicit in detailing knowledge structures. Following are several summary statements, drawn from the three theorists, on knowledge structures.

1. Knowledge structures are hierarchically organized with the more inclusive concepts at the apex and the more differentiated concepts subsumed under these broad concepts.
2. Well organized, stable and clear subsumers facilitate learning and retention of meaningful material. It is largly the nature of their organization that determines meaning in learning new material.
3. Learning material becomes anchored to existing knowledge structures via meaningful associations.
4. Where no subsumers exist to anchor new material, rote learning occurs.
5. Advance organizers, well anchored with familiar learning material, provide the basis for learning new material which otherwise may have been learned by rote.

Knowledge Structures and Curricula

> One of the goals of instruction is to help students formulate a conceptual network which will render his knowledge of specifics more useful. Such a structure should assist the student in recognizing the interrelationships of concepts and principles and also in assimilating newly acquired concepts and principles into his cognitive structure (Cooney and Henderson, 1972).

To meet this goal of providing the student with well organized, stable and clear psychological structures of knowledge implies that the curriculum be organized on the basis of structure. This however, does not suggest that the subjects need be organized along the discipline divisions. In any case facts must be related to facts to form concepts, concepts must be related to concepts to form conceptual schemes, and these must be meaningfully interrelated to yield theories and subsets of theories. Curricula designed either on the basis of principles and theories of a discipline or on conceptual schemes, in an inter-disciplinary fashion, are based on the concept of structure.

The disciplines provide a ready resource of knowledge structures for curriculum development. Schwab (1964) identifies some advantages that accrue from a knowledge of the disciplines.

> To identify the disciplines which constitute contemporary knowledge is to identify the various materials which constitute the resources of education and its obligations. To locate the relation of these disciplines to one another is to locate one important factor which determines what may be joined together for purposes of instruction, what should be held apart, and in what sequence they

may best be taught (p.7).

Knowledge of the substantive structures of the disciplines, furthermore, suggests what problem one may face in imparting that knowledge and it provides the basis of organization of the curriculum. Familiarity with the discipline's syntactical structures makes the educator aware of the need to impart to the student the tentativeness of knowledge and the methods and procedures of validating scientific findings. Knowledge of the disciplines and their structures should be of assistance to all science curriculum designers who are cognizant of the need to emphasize structure.

Traditional Curricula

The high school science curricula of the 40's and the 50's, however, were not based on the structures of knowledge of the disciplines: physics, chemistry, and biology. They were generally taught as anthologies of separate topics, as uncoordinated surveys of some of the common phenomena ("facts") and some current "explanation" of the phenomena, with the hope that the bits and pieces of information would somehow or other turn out to be useful in the lives of the students. They were not designed to develop science studies in a way that would interrelate facts and theories (Bellack, 1964; Victor, 1969).

The curriculum writers did not usually include the scientists who were obviously very much aware of the knowledge structures of their disciplines. The writers, particularly those of the physical sciences, thus drew largely from their knowledge of the application of science in industry. Biology was presented as a pool of disjoint facts and disgarded theories. Where no overriding conceptual scheme or principle was presented to simplify the picture, the student had to resort to rote learning (Marshall and Burkman, 1966).

The PSSC, CHEM Study and BSCS Curricula

The NSF supported high school science curricula, however, are markedly different than their predecessors. Among other things they were constructed on the basis of the structures of knowledge of the respective disciplines. This was achieved by the employment of eminent scientists in organizing and writing the curricula. All three curricula emphasize big ideas from their disciplines. For example, PSSC emphasizes the two central notions of modern physics: the wave-particle duality and the modern concept of the atom (Zacharias, 1964). The concept of energy and its role in reactions, the idea of systems tending toward increase in entropy and the concept of dynamic equilibrium are fundamental ideas presented in CHEM Study. The BSCS versions are organized by nine content themes. (Marshall and Burkman, 1966).

The Unified and Integrated Curricula

The structured approach is also employed in the organization of unified and integrated science curricula. The Center for Unified Science Education (1973) differentiates between unified and integrated science. Unified science is "science viewed as a whole, organized around big ideas that permeate all science, subject matter selected from a broad range of specialized sciences (p.2)" Integrated science is defined as a program that results from putting together two or more previously separate school subjects. The philosophic position generally held here is that the universe is unified and that "science" - as distinguished from "nature" - is approaching unity (Adams, 1971; Rutherford and Gardner, 1971; Slesnick and Showalter, 1961; DeRose, 1965).

An emphasis on the unified and integrated science has gained in momentum, on an international scale, within the last two decades. Several international conferences, sponsored by UNESCO have focussed on these issues with the hope of strengthening a unified front to encourage more educators, including those of the underdeveloped nations, to adopt the unified approach. The Federation for Unified Science Education (FUSE) organized in 1966, provides a focus for the clarification and advancement of the philosophy, goals and implementation of such programs.

The historical development of the unified science curricula has been summarized elsewhere (Slesnick, 1963). These programs are organized around themes generally more abstract and more encompassing than those based on the individual disciplines. They generally attempt to present the student with a knowledge structure that interlaces concepts, which in other curricula may appear to be unrelated, and in a fashion thought to be more in keeping with the real world. The seven schemes developed by NSTA (1964), which were thought to be potentially applicable to grades K-12, serve as an example of a structured basis for developing a unified science course. (It must be noted that their initial presentation was to serve the purpose of encouraging debate and clarification of issues). These are, however, thought by some educators to be too abstract to be functional, even at the high school level, and too much embedded in the physical sciences (Ausubel, 1965; Glass 1965). The themes have, since 1964, been reconsidered. While broad themes may provide anchorage for numerous. otherwise island, concepts the question of the level of abstraction must be seriously considered in the construction of such curricula.

Numerous other programs have been developed on a local level. Abstracts of some 56 unified science curricula have been prepared by the Center for Unified Science Education, an organization which disseminates the concept of unified science education and facilitates the implementation of high quality unified science programs (Showalter, 1973).

The integrated science curricula are a result of uniting two or more previously separate school subjects. In the physical sciences attempts have been made to integrate PSSC with CHEM Study or PSSC with CBA (Cheldelin and Fiasca, 1964). Other integrated curricula are summarized in a pamphlet published by The Center for Unified Science Education (1973). Unlike the unified science curricula, the integrated curriculum has a more solid foundation, though not truly unified, in the knowledge structures of the disciplines. Less interpretation is demanded of the curriculum writers.

It might be re-emphasized that the knowledge structures developed in a discipline acquire their peculiar organizational, stable, clear and functional character via a complex route of a community of intellectual, creative scientists working under paradigmic constraints. The scientist is "submerged" in his research and knowledge structuring process. The chances are reasonably good, therefore, that a student of a curriculum structured along disciplinary lines, acquires a functional knowledge structure similar in nature to that of the scientist. On the other hand although interdisciplinary sciences certainly do exist, the unified and integrated sciences are not necessarily structured along these interdisciplines. Construction of such curricula requires intermediaries who, though experts in some science, are not in a research and knowledge structuring position in unified or integrated science in an analogous fashion as are the scientists of some discipline mentioned above. The knowledge structures of the resulting curricula must therefore have a different character than those based on the disciplines.

Summary

The following statements can be made about the structures of knowledge as exemplified by the curricula in present use:

1. The traditional curricula are largely characterized by numerous disjoint facts, drawing more from technology than from the disciplines.
2. The NSF supported curricula emphasize the big ideas of their respective disciplines.

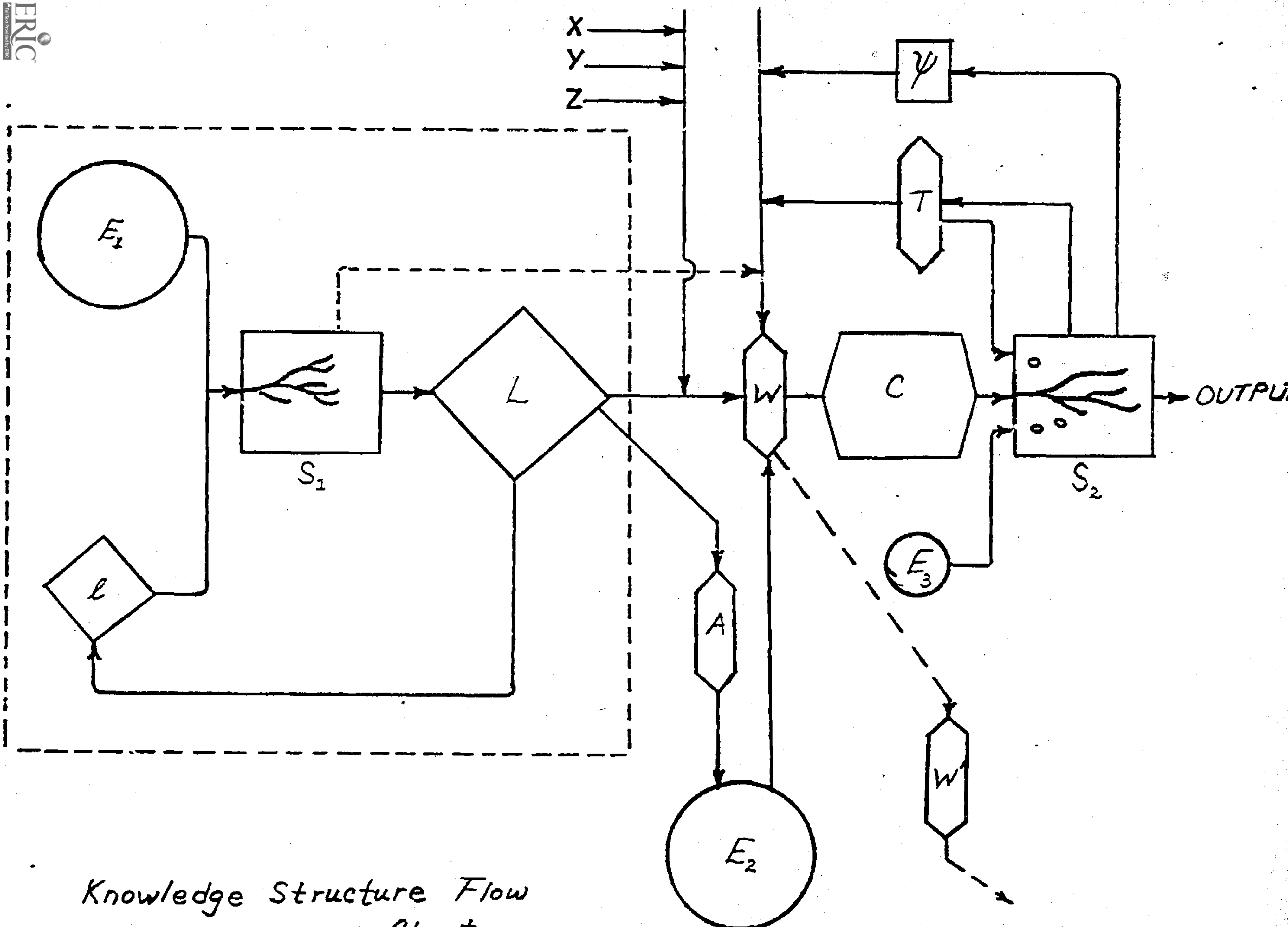
3. The unified science curricula are based on several broad conceptual schemes. Materials are drawn from all relevant disciplines as they fit into the network of concepts defined by those schemes.

4. The integrated science curricula are generally the product of a union of two or more existing subject curricula.

Summary

It has been observed in the foregoing discussions that the flow of knowledge structure from the organized, potentially meaningful environment to the formation of psychological knowledge structures of the students is rather complex. It is characterized by cyclic inductive psychological and logical processes and by several interpretations. Perhaps the model presenting knowledge structure flow from the environment to the student as shown on page 41 would help to summarize the relevant issues for this paper.

The dashed rectangle enclosing the four linked symbols represents some discipline of the knowledge structuring enterprise of science. The small rectangle labelled S_1 represents the scientist's psychological knowledge structures (Novak, et al., 1971). The empirical-logical knowledge structures (L) are generated by S_1. Since the scientist is committed to the accepted paradigm in that discipline his knowledge structures are formally similar to the empirical-logical knowledge structures, particularly those of the specific area in which he is working. The data encountered and/or extracted from the envir-



Knowledge Structure Flow Chart

onment (E_1), by the scientist are interpreted within the framework of his subsumers as well as that of the accepted paradigm. Not only does the scientist impose simplifying patterns on the environment but he also ingests newly structured knowledge in the area, 1, (generated by his peers) to provide further material for paradigm articulation, and when necessary, for paradigm replacement. This data processing and knowledge structuring affair is a continuous never ending cycle of events including both "normal" science and "revolutionary" science. X, Y and Z each represent other disciplines, similarly diagrammed as the one discussed, and feed into the system in parallel fashion.

The remaining part of the schema represents the treatment of the knowledge structures from the empirical-logical to the student's psychological knowledge structures (S_2). The curriculum writers (W), which may include science educators, teachers, and scientists, appropriately interpret the empirical-logical knowledge structures of the discipline for assimilation by the student. Criteria for interpretation derive from teacher feedback and educational learning theory. Information may additionally be drawn from the environment which includes both the natural phenomena as well as the results of technology.

The immediate psychological knowledge structure of the students then depends essentially on three major factors: the structure of the curriculum, the interpretive functioning of the teacher and the exposure to the environment. It appears that in most American schools the science curriculum is more of a determining factor of knowledge structure than is the teacher or the environment. Teachers generally tend to lean heavily on the curricula and students' exposure to the raw environment is minimal. The schema will now be used to examine the curriculum structures mentioned earlier.

The traditional curricula characterized by a multitude of disjoint facts, drew their subject material primarily from scientific applications to technology. This applies mainly to the physical sciences. Although technology does operate from broad principles, this may not be so obvious when analyzing the array of products generated by it. The broad schemes and theories of the disciplines are ignored in these curricula.

On the other hand, scientists from the various disciplines played an active part in preparing the PSSC, CHEM Study and BSCS curricula. The path from the empirical-logical knowledge structures to the curriculum is direct. Thus, some of the big ideas of the disciplines, characteristic of both the empirical-logical knowledge structures and the knowledge structures of the scientists, are well represented in these curricula.

The subject material for the preparation of a unified science curriculum is obtained from two or more disciplines schematically connected in parallel. The general frame-work here is a set of all pervading conceptual schemes interlacing all science disciplines represented and observed in/and extracted from the sciences generally. As mentioned earlier, the sythesizers of the knowledge structures here do not typify the same expertise in their field as do scientists in their disciplines. This, however, does not imply that the knowledge structures generated are not potentially functional.

In order to represent the structuring of the integrated curricula (formed from two curricula) schematically, one would need another schema similar to the one on page 40. The structures of the two curricula now feed into another interpreter symbol, W'. W' represents the curriculum writers who integrate two completed curricula by removing redundancy and by appropriately intermeshing and sequencing the materials so as to represent a fusion of the two sciences. Here again, the knowledge structures do not truly represent a discipline because it is nonexistent; they nevertheless may prove to be functional in generating meaningful research questions and their solutions.

The last two curricula types present some rather interesting questions. If a student is exposed only to unified or integrated science curricula will he be prepared to make a meaningful contribution to research? It must be mentioned that the purpose of many unified science programs is to promote scientific literacy of the non-science major. On the other hand, unified or integrated science programs are the only ones offered in some high schools (Slesnick, 1963). Should interdisciplinary sciences be initiated at the forefront of research, in the schools and colleges or should they be begun within the whole continuum? The purpose of this paper is not to resolve these issues. Further elaborations of the structuralist position may be found elsewhere (King and Brownell, 1966; Foshay, 1961); positional statements representing the unified science position are also reported elsewhere (Kliebard, 1965; Hurd, 1973; Lerner, 1964; Chisman, 1963).

HYPOTHESES CONCERNING PSYCHOLOGICAL KNOWLEDGE STRUCTURES in SCIENCE

Having traced the knowledge structuring process of science, and having outlined the high-lights of learning theory related to psychological knowledge structures and the principle structural features of some of the contemporary high school science curricula, what questions may one ask about psychological knowledge structures? Following are a set of hypotheses concerning psychological knowledge structures drawn from the present study which, if tested, may illumine the knowledge structuring process in science education:

1. The student that is unfamiliar with a given subject matter will have no psychological knowledge structures in this area.
2. The student that is familiar with a given subject matter will have psychological knowledge structures in this area which are hierarchically organized; the general idea subsumes the specifics.
3. The nature of the psychological knowledge structure, whether it is organized, stable and clear, determines its functional characteristics in learning new material.
4. A student that has no psychological knowledge structures in an area and is exposed to new material in this area, will develop a knowledge structure in which the new material is divorced or unassociated with his existing structures.
5. New knowledge structures that have no anchorage in existing structures will not be retained very long.

6. Newly acquired knowledge structures should be retained longer if anchored with meaningful associations.

7. New material is anchored in existing knowledge structures via meaningful associations between elements of the structure.

8. As a student becomes more familiar with a subject matter, the association between entities of the structure should become more cohesive.

9. As a student becomes more familiar with a subject matter, his psychological knowledge structures should more closely approximate that of the subject matter source (whether teacher and/or curriculum).

10. A dynamic switch in a subject's knowledge structures should be demonstrable as new generalizations replace the old. Frequently subject material is presented in simplified fashion so that the student can comprehend the concept. Later a more generalized presentation is given. Examples might be the atom or relativity. The whole phenomenon of the gestalt switch, as elaborated by Kuhn (1962), could perhaps be given more emphasis in educational psychology, particularly in Ausubel's subsumption theory.

11. Knowledge structures acquired via discovery learning should be more cohesive than those acquired via reception learning (Bruner, 1960).

12. Specific knowledge structures should be generally the same for traditional, NSF supported, unified and integrated

curricula.

13. Knowledge structures of broad concepts should be generally non-existent in the student enrolled in the traditional curriculum.

14. The knowledge structure of the student enrolled in the unified science curriculum should be better organized stable and clear than that of the student enrolled in an integrated course, when considering broad schemes.

15. The knowledge structures of the student enrolled in the integrated science curriculum should be better organized more stable and clear than that of the student enrolled in an NSF curriculum, when considering broad schemes.

16. The knowledge structures of a student enrolled in an NSF supported curriculum should more nearly approximate that of a corresponding practicing scientist than that of a student enrolled in any other curriculum.

17.. The knowledge structures of a student enrolled in an integrated science course should more nearly approximate that of a practicing scientist than that of a student enrolled in a unified science curriculum.

18. The similarity of psychological knowledge structures in science should be greater for adjacent pairs than that of any other pairs of the ordered set of curriculum agents: scientists, writers, teachers and students.

REVIEW of RESEARCH

This section will review those studies reported in the literature which attempt directly to identify and analyze perceptions of knowledge structures in science. Although some of the studies speak to the hypotheses arrived at in the previous section, it will be observed generally that there is a paucity of research in this area. This is perhaps due to the recent emergence of the structure emphasis in curriculum development. The earliest research studies in the area were initiated about a decade ago.

The techniques generally employed to operationalize the measurement of psychological structures of knowledge in science are: the word association (WA) test (either free or constrained), the F-sort, the similarity rating (SR) test, ratio judgements and the semantic differential. Although some of these techniques appear to be quite well established in the research in the area, there still is some groping to perfect the techniques and analytic tools.

Since the type of research reported here deviates considerably from standard research studies reported in the science education journals the studies will be presented in considerable detail. First those studies concerned with sampling students' perceptions of knowledge structures of a rather small population of concepts will be considered. These focus on concepts in Newtonian Mechanics. Secondly, studies focussing on perceptions of knowledge structures of more broad and/or more numerous sets of concepts will be considered. Finally, a study that concerns the relative perceptions of curriculum agental groups of a discipline's structure will be considered. The analyses will then be discussed within the context of the hypotheses listed earlier.

Psychological Knowledge Structures in Newtonian Mechanics

Research Series by Paul E. Johnson

Paul E. Johnson has carried out a series of investigations of high school students' psychological knowledge structures in physics by administering word association (WA) tests and similarity rating (SR) tests. His studies have evolved from the single use of the WA with four different groups to the use of WA and SR tests comparing a treatment groups' perception with that of a control group. His mode of analysis also evolved over the period of the five studies. These studies will now be presented in chronological order.

In the first study Johnson (1964) administered a WA test to four different groups of varying degrees of involvement in physics - subjects that were currently enrolled in physics, subjects who had taken physics, subjects who were planning to take physics and subjects who were not planning to take physics. The 18 stimuli for the WA test were: volume, density, weight, acceleration, mass, energy, velocity, force, distance, work, power, inertia, momentum, pressure, temperature, speed, time and impulse. The subjects were allowed five seconds to respond with the first word the stimulus made them think of.

Mann-Whitney tests of significance (these were used due to lack of homogeneous variances of distribution) of the number of stimuli words used as response words indicated significant differences between all group pairs. The order, highest to lowest, in response frequency was: the group currently taking physics, the group that had taken physics, the group that planned to take physics, and the group not planning to take physics. Indices of interitem associative strength of the physics concepts yielded the same pattern. An intersection coefficient, indicating the strength of similarity between compared concepts, indicated meaningful relations. However, Newton's second law did not cluster.

Johnson states "It is possible to say on the basis of the present data that subjects move from one concept to another by means of mediated equalities (p.87)".

In a second study Johnson (1965) compared the performances of two randomly equated groups of high school students on both a WA test and a physics problem solving test. One group had the WA test first while the other had the problem solving test first. In the WA test the students were asked to respond with the first physics word that came to mind. The time allotted for response to nine stimulus words was two minutes.

The investigator found that those subjects who took the WA test before the problem test solved significantly more problems than did the subjects who received the problem test first. The subjects who gave a relatively large number of problem-relevant responses in the WA test solved more problems than the subjects that formed few such associations. Furthermore, those subjects that had the problem test before the WA test gave significantly more stimulus-list words as responses than subjects who had the WA test first. The subjects who had the problem test first also gave significantly more problem-relevant associations than the subjects who had the WA test first.

In another experiment 24 high school students were divided into two equal groups on the basis of their achievement in Newtonian Mechanics. In the WA test that was administered, the subjects were given one minute to list as many response words as came to mind for each stimulus word. Each stimulus word appeared 24 times on a page so that the subjects would respond to the stimulus word rather than engaging in chaining by responding to response words. The 14 stimulus words represented the maximum frequency range of relevant concepts in a standard physics text. The subjects were also asked to compare each of the paired stimulus words on a seven point similar-dissimilar scale.

The high achievers gave significantly more responses per stimulus word than the low achievers, and the high-frequency words elicited significantly more responses from subjects than the low frequency words. Furthermore, the frequency response of the high achievers was more highly correlated with the frequency of stimulus words in the text than was that of the low achievers. Johnson states that those words which occurred frequently in the written materials were more meaningful for both high and low achievers than words which occurred infrequently.

Also, both frequently and infrequently occurring words were more meaningful for high achievers than for low achievers.

It was found that stimulus words used in equations were more frequently interrelated by high achievers than low achievers. Furthermore, these constrained responses generally appeared early in the subjects' response hierarchy, especially for the high achievers. Although the general degree of relationship between the WA test and the SR test was high for both high and low achievers, there was considerable variation between the two groups for individual concepts.

The associations of concepts formed in the cognitive structures of the subjects depend both on past experience and exposure to curriculum materials. The author posits the value of a unique language for physics when he states

> Perhaps knowledge of the structure of a subject such as Newtonian Mechanics would proceed more rapidly than it does if more of the words which represent its concepts were not related to outside patterns of usage but were instead learned simply as they are related to one another by means of the formal constraints in the subject matter (Johnson, 1967, p.83).

In a fourth study Johnson (1969) replicated his 1967 study except that in the 1969 study the subjects were subjected to a treatment in Newtonian Mechanics and were therefore given pre and post tests. The purpose of this study was to relate verbal associations and judged similarity among words, which represent physics concepts, to empirical characteristics of the language constructed to communicate these concepts. The

WA and SR tests were administered, at both pre and post periods, as in the 1967 study.

It was observed that subjects gave significantly more responses to the 14 stimulus words on the posttest than they did on the pretest. The difference between the two test conditions was significantly greater for the high-frequency words. Again, the meaningfulness of the words increased.

The frequency with which subjects responded with words from the stimulus list increased significantly. (The rank-order correlation between stimulus-list word frequency responses and the frequency occurence in the test materials was .60, with $p < .05$). The frequency with which the 28 pairs of words (comprised of five relational and three operational concepts) cooccured in sentences in the test correlated significantly with their cooccurence in the post WA test.

It was found that the judged similarity of the eight relational and operational words was relatively stable from pretest to postest. The subjects must have had some familiarity with the concepts from every day usage at pretest time. The rank order correlations between relatedness coefficients and similarity judgements on the pretest and postest were significant.

Johnson concludes that after the treatment in Newtonian Mechanics the operationally defined concepts are associatively as well as perceptually more similar to its relationally defined concepts than before this experience. This suggests

that the common-sense or prescientific

> knowledge of relationally defined concepts in this subject matter is now related to immediate experience and can function in the perception of that experience in a manner which is consistent with the perceptions embodied in Newtonian Mechanics (p.39).

In a fifth study reviewed by Shavelson (1970), though not reported in the literature, Johnson re-analyzed the 1967 data with factor analytic techniques. For high achievers the data was interpretable with two factors: distance-time and mass-no mass. The configuration of concepts for the low achievers were not describable in terms of motion and mass.

Similarity Judgements with Respect to Concept Difficulty

Kass (1969) analyzed high school students' perceptions of concept difficulty. She administered a paired comparison task to 353 grade twelve physics students. With 20 stimuli, a total of 190 paired comparisons were made on a nine point difficulty scale. These stimuli, taken from mechanics, were comprised of names of equations or principles with appended definitions. A physics achievement test was also administered. Multidimensional scaling techniques were used to analyze both the average as well as the individual viewpoint dimensions. Analyses were carried out with each of three randomly identified groups as a check on reliability. Little difference was found between the individual and the average viewpoints. However, it was found that the average perceptual space could be characterized in terms of four or five dimensions, of which two were identifiable. One dimension was defined by motion-static characteristics in which the rotational motion loaded as very difficult (or large negative), uniform acceleration loaded as less difficult and static states loaded as least difficult (or large positive). Another dimension was defined as a vector-no vector continuum. Velocity, projectile motion, moments and composition and resolution of forces had high negative loadings while work, power and potential energy had large positive loadings. The other dimensions were rather difficult to identify. Considerable stability existed in the configurations from group to group.

Psychological Knowledge Structure Change and Comparison with Curriculum

Shavelson (1970) reported a study in which the changing knowledge structural patterns of a treatment group were compared both with those of a control group and with the content structure of the instructional materials. The 40 high school students, 28 of which formed the treatment group, were pretested with a physics achievement test, several aptitude tests and a word association (WA) test. The 14 stimulus words for the WA, taken from Newtonian Mechanics, were the same as those used by Johnson (1967). In the WA the students were to "think like physicists" and were to record all words that came to mind within the time allotted. One stimulus word was repeated per page in a manner simular to Johnson's (1967) procedure. The treatment group was given one lesson in Newtonian Mechanics on each of five consecutive days. A WA test was administered after each lesson.

The control group received an equal number of WA tests but within a three day period. Alternate forms of the physics achievement test were administered after the treatment.

The content and the WA data were converted into distance matrices. Digraph theory, in which the elements or concepts were represented by points and the relationships by directed lines, was used to transform the content material into a distance matrix. The relatedness coefficient (RC) by Garskoff and Houston were used to transform the WA data into distance matrices; the entries were the median of the student distributions.

Shavelson observed that as time progressed the psychological knowledge structure of the treatment Ss became more "tight", more nearly approximating that of the content. Further evidence seemed to indicate that those students performing well on the Hidden Figures aptitude test and the physics achievement posttest stored the information in equation form in memory. These "chunks" of information were readily retrievable for solving the physics problems.

Models and Psychological Knowledge Structures

Johnson, Cox and Curran have identified geometric models, both two - and three - dimensional, of concepts in mechanics. They have compared the psychological knowledge structures in this area with these models and have met with considerable success.

A rather interesting study was carried out by Johnson, Cox and Curran (1970) in which a three dimensional geometric model was hypothesized as representative of the psychological space of certain physics concepts. The positive axis of each dimension represented the integral with respect to some operational entity.. The negative axis represented the derivative with respect to that entity. Performance of a single operation corresponded to motion of one unit distance along the axis. The three operational quantities were distance, time, and mass. The origin was defined as distance. The authors state that this

> approach is based upon the assumption that the study of internal representations of physical concepts must focus upon the relationship between the structure among external representations of these concepts and the structures among their corresponding internal representations (p.245).

Fifty college physics majors rated the similarity of six concepts on a seven point rating scale and provided response words to these six concepts on a WA test. Procedures used to collect the data were similar to those used earlier by Johnson (1969).

The mean rating scale judgements between pairs of words in the similarity rating test and the mean proportion of associative responses each pair of concept words had in common on the WA test were both used in the analysis. Multidimensional scaling techniques yielded three dimensional configurations for both measures and for both Euclidean and city-block metrics and a two-dimensional solution for both tests using the Euclidean metric only.

The scaling solution in two dimensions with Euclidean distance indicated clusters of mass and no mass, and clusters of uniform motion and acceleration. These partitioned patterns are similar to those of the three dimensional geometric model. The three-dimensional solution was a very close fit to the hypothetical geometric model. (Rank-order correlations between distances in the geometric model and distances in the three-dimensional scaling solution for both tests and for both metrics were .85 or more). The two tests employed yield very similar results. (Correlations between scaled distances on both tests were .87 or more).

The authors conclude that although the two-dimensional solution can be interpreted the three-dimensional solution is more parsimonious because it agrees with the model and it has the capability of generating a large variety of stimulus points.

Johnson, et al. (1971) state that while the writings of Kuhn, Nagel and Pearson are potentially rich in their implications for the understanding of the process of science, they are not readily amenable to the study of concept acquisition and understanding in science. The authors present a two-dimensional model comparing relational and operational Newtonian Mechanics concepts. The concept of power, for example, can be thought of as a combination of work and time. They hypothesize that the dominant word associations of given concepts should correlate distancewise with those concepts in the geometric model. And furthermore, similarity measures should generate distance quantities that agree with the model.

Forty-nine college physics majors were given three tests:

a free-association (FA) test, a constrained-association test, and a similarity-rating test. In the FA test the nine stimulus words were printed once at the top of each page followed by 25 blanks. (This procedure is a departure from the 1967 study). The subjects were asked to write as many words as they could which the stimulus word brought to mind. In the CA test the subjects were constrained to respond with nouns only.

The authors observed that the frequencies of responses tended to match the two-dimensional model. The stimulus words in the middle of the model elicited more responses than the end words in both FA and CA tests. There was a high relation between the results of the FA and CA tests. Both test results were highly related to the geometric model. The correlations were .84 and .81 for the FA and CA tests respectively. The results of the similarity ratings were also highly related to the model. Both the FA and the CA tests correlated highly with the similarity test.

The authors conclude that their geometric model may be good representation of the psychological knowledge structures of the subjects.

Psychological Knowledge Structures of Larger Concept Population Pools

Gardner and Johnson (1968) attempted to identify the changing knowledge structures of seventh grade students as related to exposure to a newly developed behavioral science course. They emphasize the problem of expressing logical structures in a form that is meaningful to the students. Bruner's hypothesis that "any subject can be taught effectively in some intellectually honest form to any child at any stage of development (Bruner, 1961, p.33)" is far from being empirically established. They selected 25 key concepts, around which the subject material was organized, and administered these in a WA test to the subjects both as a pre and post test. The subjects were to respond with the first word that came to mind.

Although expected common response frequencies did not increase markedly over the treatment, there were some associative strength changes that were attributable to the instruction. It was found that those concepts considered to be most important were the least stable (showed the greatest change in associative meaning) across experience in the subject matter. The changes of both the more important as well as the least important stimulus words were mixed. In some instances interstimulus response increased, in other cases it diminished.

The authors feel that the study may have implications for curriculum revision. They suggest that asking students what they can do with various representations of concepts taken from the subject matter, rather than asking whether the students learned what they had been taught or what they were supposed to learn, has considerable merit. Gardner and Johnson conclude

> To ask whether a student has learned what he was supposed to learn about these concepts presupposes that one has some notion of what the student could learn from the materials of the subject matter which represented them; and in the early stages of curriculum

> development, it is extremely difficult to be sure that what curriculum writers produce by way of a subject-matter model is in any sense a reasonable model of what students actually learn. It is our feeling that questions which have to do simply with a student's capabilities provide more information concerning the acquisition of various representations which may be given to a subject matter for purposes of instruction and also a better understanding of the psychological processes involved in the learning and understanding of its concepts (p.410).

In a monograph, A Methodology for the Analysis of Cognitive Structure, Thomas J. Johnson (1969) briefly high-lights a study in which 50 physics concept stimulus words were sorted by two different groups of college students. These concepts, taken from a broader population than those used in earlier reported studies by Paul E. Johnson, included words from the areas of mechanics, electricity and magnetism, optics, wave phenomena, states of matter, heat, measurements, and atomic and nuclear physics. One of the groups was about to begin the physics course while the other had completed it. There was no indication of whether or not the groups were initially equivalent.

The categorical data was analyzed with a latent partition analysis procedure and yielded 12 categories one of which appeared to be a "garbage" category. A multidimensional scaling of these categories yielded configurations which indicated slight differences in the sorting results of the two groups. The students who had taken the course manifested somewhat greater differentiation between the concepts.

In an exploratory study Toews (1973b)* administered 39 concept descriptors, drawn from the Brandwein Series Concepts in Science 6, to 47 grade eight students as a sorting activity. The students had used this text earlier and were currently enrolled in a science course that used the Brandwein Series as reference books. The procedures were similar to those carried out by Miller et al. (1967). A second test, analogous to a Q-sort on the same 39 concepts, was administered after the F-sort. Four choices for concept classification were drawn from the curriculum.

The categorical data was analyzed with a latent partition analysis (LPA) procedure (Wiley, 1967; Wolf, 1968) and with a hierarchical clustering analysis (HCA) procedure (Johnson, 1967). A similarity index was developed by the author which allowed a comparison between the F-sort data and some standard.

The LPA yielded seven categories. The pairing of concepts was such that, on the basis of the similarity index, increased conformity to the seven categories implied increased conformity to the Brandwein standard. The HCA agreed well with the LPA, but in addition, provided a meaningful pattern of concept hierarchy.

The results seemed to indicate that subjects frequently responded to single catchwords rather than to complete concept statements.

Comparative Psychological Knowledge Structures of Curriculum Agental Groups

In his dissertation, The Mapping of Concepts, Taylor (1966) attempted to establish a technique that would facilitate

*Submitted to the Journal of Educational Measurement description and exploration of a variety of educational and psychological situations that concerned differences of personal viewpoint. In the specific application of his methodology, the structure of biology, as perceived by biology experts, curriculum writers, and teachers (agental groups in curriculum development) were sought and compared.

Four hundred concepts and topics in biology were selected from 11 biology text books and reduced to 95. These were then categorized by a group of judges. Nine themes resulted which were identical to those of BSCS. Further a set of meta-objectives were identified which while subsuming the 95 concepts and the nine themes, were to apply to more than one discipline.

Each of the 110 teachers, 36 writers and 48 biologists performed two tasks. The tasks were: pair comparison of the meta-objectives based on a preference scale, semantic differential on these objectives, categorical sorting of the 95 items, and making ratio judgements using the nine themes (there were 84 possible trials). All data was transformed for purposes of factorization and intercomparison using the standard Procrustes equation. The analyses generally indicated that the psychological knowledge structures of the specialists was more similar to that of the curriculum writers than that of the teachers. Furthermore, the teachers generally viewed comparison of items in terms of the practical while the scientists were more theoretical.

Criticism of Research and Comparison to Hypotheses

Perhaps the most serious criticism of these studies, from the educator's point of view, is that despite the relevance of structure in the educational arena, there is little attempt in rooting such form of research in educational theory. There may be a need of generating a theory that pertains specifically to these issues. However, it appears to this author that the hypotheses generated from the knowledge structuring enterprize of science, extant learning theory and current curriculum designs should provide a meaningful beginning. The reviewed literature will now be considered in light of these hypotheses.

Several studies indicate that psychological knowledge structures were virtually lacking in students that were unfamiliar with the subject matter. Johnson (1964) observed this to be the case with students not having taken, and not planning to take physics. This does not imply that physics concept stimulus words in a WA test did not elicit any response. The response words were comprised of everyday nontechnical terms, which may suggest some structure, though not in the academic sense considered here. The control group in Shavelson's (1970) study generated few response words in the WA test that were part of the stimulus list.

A considerable difference, in knowledge structures, was observed between those unfamiliar with the subject materials and those familiar with the subject materials. The results of Johnson's (1964) study lend support ot the first part of Hypothesis 2. (The student that is familiar with a given subject matter will have psychological knowledge structures in this area which are hierarchically organized; the general idea subsumes the specifics). In addition, it can be observed that the degree of structure, as measured by the WA test, is proportional to familiarity with the subject material. Although the students writing the problem test first, had familiarity with the knowledge structure of Newtonian Mechanics, writing this test first provided a review which reinstated immediate familiarity with the structure (Johnson, 1965). They thus performed better on the WA test than the group writing the WA test first. The higher achievement group (Johnson, 1967) and the treatment group (Johnson, 1969) both demonstrated superior structure to their counterparts. The question of hierarchy is not addressed in the studies. The hierarchies of the response lists in the WA tests represent degree of association and do not speak to the structural issues as delineated in Ausubel's subsumption theory.

None of the studies address Hypothesis 3 in an experimental sense. (The nature of the psychological knowledge structure, whether it is organized, stable and clear, determines its functional characteristics in learning new material). It was observed, however, that previously established psychological knowledge structures (though these were not directly identified) had an effect on the knowledge structuring process during treatment. Previously established structures tended to interfere with the treatment process (Johnson, 1967; Gardner and Johnson, 1968).

In the first study reported by Johnson (1964) the psychological knowledge structure of the group that had taken a physics test scored second. Although, as a group, they had retained most of that structure, one needs to examine initial structures and perhaps individual differences to address Hypothesis 6. (New knowledge structures that are well anchored with meaningful associations should be retained long).

Several studies indicated that one can infer that new material is anchored in existing knowledge structures via meaningful associations between elements of the structure. Whereas, initial response words to stimulus words at pretest time were generally nontechnical, at posttest time they generally elicited other stimulus words (Johnson, 1967; Savelson, 1970; Gardner and Johnson, 1968). This suggests that the new set of technical terms acquired a structure while retaining anchorage in previously existing structures.

A noticeable change in psychological knowledge structure was observed in several studies as students gained familiarity with the subject material. This was particularly evident in Shavelson's (1970) study in which the knowledge structures of the treatment group steadily became "tighter". Johnson (1967) and Shavelson (1970) observed clustering of equation concepts into tight entities. Not only were they readily retrievable but they proved to be functional in problem solving. Johnson (1969) states that after the instruction the treatment group manifested somewhat greater differentiation between the concepts.

A few studies indicated reasonably good agreement between the psychological knowledge structures of the students and knowledge structures of the curriculum (Johnson, et al., 1971; Shavelson, 1970; Toews, 1973b; Taylor, 1966). A group of judges in Taylor's study were able to arrive at the BSCS themes in categorizing 95 concepts. The distance between the two structures steadily diminished as students, in Shavelson's study, continued with the instruction.

Taylor (1966) observed that the perceptions of knowledge structure of curriculum writers were between those of the specialists and the teachers. This in part supports Hypothesis 18. (The similarity of psychological knowledge structures in science should be greater for adjacent pairs than that of any other pairs of the ordered set of curriculum agents: scientists, writers, teachers and students).

SUGGESTIONS for FURTHER RESEARCH

Numerous issues raised by the hypotheses have not been addressed by the research literature. Further suggestions for research questions will now be presented.

1. How do psychological knowledge structures match with theory? Can they be demonstrated to be hierarchically organized as suggested by Ausubel? Can the question of rote learning, non-anchorage and retention be demonstrated by direct measurement?

2. Can the phenomenon of the "gestalt switch" in the change of perception of knowledge structure be monitored during a learning process? This may elucidate the question of whether it is more pedagogically sound to initially present limited (but wrong) theories in respect of the student's maturational level rather than approaching the goal directly.

3. Bruner believes that better psychological knowledge structures are built as students are allowed to discover "truth". This certainly is not in agreement with Ausubel's view. He emphasizes the importance of efficiency in meaningful verbal learning, and also outlines how materials need to be structured. Would the monitoring of structural change and growth of knowledge in the student shed light on learning procedures?

4. How do the various curricula affect structure? What is an acceptable structure? Mention has been made of the pros and cons of some of the extant curricula. Are the conceptual schemes of some of the unified science curricula too

abstract to be functional?

5. Attempts have been made to identify subgroups' perceptions of knowledge structures. (Kass, 1969; Johnson, 1967). Techniques need to be refined which will relate the structure, as perceived by an individual, to other cognitive variables. The similarity index developed by Toews (1973a)* appears to be a step in this direction). Further developments are needed in this area.

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