; cases occur when the person doing the reasoning is not aware that he 's any relevant general principles. What in fact happens, we believe, is two s. First there is something akin to our mayonnaise example: reasoning by gy. Second, comes the examination of several examples and a generaliza- A general principle can be considered to be one in which the schema has of its constant terms replaced with variables (the variables will have raints placed upon the set of concepts which may be used to fill them).

: process by which one takes specific knowledge about a particular instance :oncept or of an experience and generalizes it to apply to a larger class of ·iences is one that needs a good deal of study. One suspects that this alization process is at the heart of much of our everyday operations in ı new situations must be dealt with by the experience gained from old ones. ıing by analogy, learning by modification of existing schemata, the use and ›retation of metaphor, and functional reasoning would all appear to be d examples of this generalization of knowledge. As we gain in our under- ing of the structures of human memory and in the ways by which the ledge structures are acquired, modified, and used, we will come to enrich nderstanding of learning, of teaching, and of the human use of knowledge.

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Abstract Conceptual Knowledge: How We Know What We Know

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INTRODUCTION

The task of developing a psychology of instruction is formidable because we must first understand the nature of knowledge, how it is acquired, under what conditions it might be taught, and the signs by which its attainment might be celebrated. Of course, our task would be foredoomed if every area of knowledge were so distinctive in its requirements on the human mind that completely different cognitive processes were invoked in each case. If so, then the most help educators might realistically expect from psychologists would be a pluralism of principles consisting of independent sets of heuristic tricks, especially tailored for each area of pedagogical focus.

Clearly, the working hypothesis which best serves both psychology and education assumes that knowledge-gathering processes of mind are essentially the same across all disciplines, that any differences will be in detail rather than principle. Let us then begin by posing the central problem for a cognitive theory of instruction in a way that presupposes this working hypothesis: *what is the nature of the general cognitive capacity that underlies all knowledge acquisition?* It is to this question that this chapter is addressed.

THE ABSTRACT NATURE OF CONCEPTS

A basic characteristic of human intelligence is the ability to formulate abstract conceptual knowledge about objects and events. Abstract conceptual knowledge is exemplified when we can deal appropriately with novel instances of a concept, that is, when our knowledge goes beyond just those instances experienced.

There is abundant evidence that our knowledge of language must be abstract given the novelty that must be dealt with. Indeed, the role of novel events in language has long been recognized by linguists. Sentences are almost always novel events. To verify this fact you need only pick at random a sentence in a book and then continue through the book until the sentence is repeated. Unless you have picked a cliché or a thematic sentence, it is unlikely that the sentence will reoccur. We readily admit that most sentences are novel, but what about the elements from which sentences are constructed? These elements must be the same in order for us to understand sentences. Further examination, however, shows that words too are typically novel events. The apparent physical sameness of words is an illusion supported by the use of printing presses. If we consider handwriting, we find a great deal of variation in the construction of letters and words. The novelty of words becomes even more clear when we think of the same word spoken by different speakers, male and female, child and adult, or by the same speaker when he is shouting or whispering. Words, like sentences, are typically novel events. To say that words are novel events may be incorrect in some instances. We have heard our friends use the same words many times, our own names being a case in point. The importance of the argument for novelty is to illustrate that this repetition is not necessary for our understanding of words; thus our ability to recognize words is not a function of having experienced that particular *physical event* before.

Greenburg and Jenkins (1964) demonstrate an even more striking example of the capacity to deal with novel instances of a class. They found that English speakers could deal appropriately with novel sequences of English phonemes. Sequences of Phonemes in English are subject to powerful constraints described by rule structures for syllable and word formation. If we randomly sample strings of English phonemes we will produce three types of strings: strings which are actual English syllables or words; strings which violate the rules for English syllables and word construction and therefore are not English syllables or words; and finally, strings which are in accord with English rule structure, but are not found in English. Given only consonant–vowel–consonant (CVC) strings we all recognize *cat* as an actual English word and *cah* as clearly not an English word. However, what about the strings *dib* and *lutt?* Both of these CVCs are in accord with English rules of syllable construction. *Dib* is in fact an actual English word. Consequently, Greenberg and Jenkins constructed a measure of distance from English, based upon the rules of English syllable construction, which accurately predicted subjects' judgments of novel strings of phonemes. The subjects' judgments about novel strings of phonemes were consistent and predictable on the basis of linguistic rules for syllable construction in English.

This research clearly demonstrates that the knowledge, on the basis of which English speakers recognize and construct English syllables and words, is abstract in the sense that it is not knowledge of particular physical events, but rather knowledge about systems of abstract relationships. One's ability to recognize sequences of phonemes not experienced before as acceptable or unacceptable English strings demonstrates knowledge of rules of sequencing of phonemes, that is, abstract conceptual knowledge which allows us to recognize and produce novel events.

But phonemes too are abstract classes of events which cannot be specified in terms of common physical elements. Research in the perception of speech has shown that the same phonemes are specified by different physical events in different contexts and that the same physical event can specify different phonemes in different contexts (Fant, 1964; Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). So, with phonemes too, the basis of recognition is knowledge of a code or system of relationships, not knowledge of particular physical elements. As we have seen, breaking language events into smaller and smaller elements does not result in a level of analysis based upon particular physical elements. Rather, at each level we find still another system of abstract relations which is necessary to specify the nature or meaning of particular physical events.

Similarly, we are able to recognize a melody played on a piano even though previously we have only experienced instances of that melody played on other instruments, or by an orchestra, or even hummed. To do so, therefore, we must have an abstract concept of the melody that specifies the isomorphism existing among the various instances. Often we are able to recognize that a painting is executed in the style of impressionism or by a particular artist, say Cezanne, even though we have never seen that particular work before. To do so we must have an abstract concept that specifies the style of the school or artist such that the instances, novel ones included, are seen as similar. Thus, there seems to be ample reason to conclude that concepts are not necessarily based upon knowledge of particular physical events, nor upon physical units, elements, or features, since instances of many concepts are only abstractly related.

GENERATIVE CONCEPTS

Due to their generality, abstract concepts apply to a potentially infinite equivalence class of instances. However, this fact poses a serious problem for a cognitive theory bent upon explaining how they are acquired. Since one's experience is with but a sample of the entire set of instances to which such concepts refer, several puzzling questions arise: First, how can experience with a subset of objects or events lead to knowledge of the whole set to which it belongs? There is a problem of explaining how *some* part of a structure can be equal to the whole structure. Indeed, the claim that *some* can, under certain circumstances, be equivalent to *all* seems to involve a logical contradiction. That it does not, fortunately for cognitive theory, can be amply illustrated in many different areas of conceptual knowledge. In a moment, we will illustrate this fact from examples drawn from three distinct fields—mathematics, linguistics, and perceptual psychology.

A second crucial question that must be answered, given a precise answer to the first, concerns the nature of the subset that can provide the knowledge necessary to deal with the entire set. Will just any subset of instances do, or must the subset be a certain size or quality? In other words, how do instances of a concept qualify as exemplary cases of the concept? A precise answer to this last question has quite obvious implications for the selection of effective instructional material for teaching concepts.

Generative concepts in mathematics. In mathematics the concept of an infinite set provides a structure for which it is true that a proper subset is equal to the total set. Cantor proposed this definition of the infinite when he discovered that a subset of all natural numbers, such as the even integers, can be placed into a one-to-one relationship with the total set of integers. But a more relevant case for our purposes is the problem of providing a precise description for an infinite class of objects. By a precise description is meant a finite specification of every instance of the infinite class.

A moment's reflection suffices to conclude that so-called *nominal* concepts are quite inadequate for this purpose since it is impossible to ostensively define an infinite class, say by pointing to each element. Hence the label "infinity" could not be consistently applied since finite enumeration will not discrimate between classes just a little larger than the ostensive count and ones infinitely larger.

For similar reasons so-called *attributive* concepts of infinite classes are not possible since the attempt to abstract common features from all members of such classes fails. If not every member of an infinite class is surveyed by a process of finite abstraction, then a potentially infinite number of cases may exist which fail to exibit the attribute common to the finite subset actually experienced. Thus, the learning of concepts that refer to classes with a potentially infinite number of members such as trees, people, red stars, cannot be adequately explained by a cognitive process involving finite abstraction. The process of abstraction postulated to explain the acquisition of abstract concepts must work in some other way. As a mill for abstract knowledge, it must take a finite set of exemplars as grist for producing concepts of infinite extension.

This problem has perplexed philosophers for many centuries, leading some empiricists and nominalists to propose that in fact no concept of an infinite class is really possible. Their argument was based upon the belief that since finite abstraction is the means by which all concepts are formed, then the concept of

the infinite must be a negative concept referring only to our ignorance regarding the exact size of a very large class which had been indeterminately surveyed by the senses. This belief constitutes a refusal to recognize the creative capacity of human intellignece and led the empiricists to a theory of knowledge founded upon associative principles—principles which define knowledge as nothing more than the association of memoranda of past sense impressions—what Dewey (1939) rightfully called "dead" ideas because they cannot grow.

Infinite structures can only be represented by finite means if the finite means are creative, in the sense that a schema exists by which the totality of the structure can be specified by some appropriate finite part of the structure. Such a schema by which the whole can be generalized from an appropriate part can be called a *generative* principle, while the appropriate part can be called a generating substructure or just *generator* for short. That a structural totality can be specified by a generator *plus* a set of generative principles can usually be verified by the principle of mathematical induction.

Consider the problem of how one comes to know the concept of natural numbers. Two stages seem to be involved: one must first learn the set of numerals 0, 1, 2, . . . , 9 as well as a system of syntactic rules by which they may be concatenated to form successively ordered pairs (e.g., 10, 11, . . . , 99), triples (e.g., 100, 101, . . . 999), etc. The number of numerical strings is, of course, potentially infinite. Hence the numeral set 0, 1, 2, . . . , 9 constitutes the generator which potentially yields all possible well-ordered numerical strings when the appropriate generative rules of the grammar are applied.

The second stage in acquiring the concept of natural numbers entails *inter alia*, not only knowledge of the grammar for numerical labels, but knowledge of the *closure* of arithmetic operations by which (*a*) any number can be shown to be a logical product of an arithmetic operation applied to a pair of numbers e.g., $1 + 0 = 1$, $1 + 1 = 2$, $1 + 2 = 3$, . . . ,and (*b*) any logical product of numbers always yields numbers.

Indeed, it does not take children long to realize that any combination or permutation of the members of the generator set (0, 1, 2, . . . , 9) yields a valid number. For example, is 9701 an instance of the concept of natural number? Of course, you will recognize it as a valid instance. But how do you know? Have you ever seen this number before? Does it matter? Unless it is part of an old phone number, address, or some serial number that you have frequently dealt with, then you probably have no idea whether it is a familiar or novel instance of the concept of natural number. Nevertheless, one knows immediately that it is an instance, presumably because one's knowledge of strings of numerals is as abstract as that for English sentences.

Generative linguistic knowledge. A similar line of argument can be developed with respect to the best way to characterize a speaker's knowledge of his native language. The problem is: "how do we acquire the linguistic competence to comprehend sentences that have never before been experienced?" For instance, it is unlikely that you have ever experienced the following sentence: *the impish monkey climbed upon the crystal chandelier, gingerly peeled the crepes from the ceiling, and threw them at the furious chef.* This fact, however, in no way diminishes your ability to recognize it as a grammatical, if novel, sentence.

Whatever the precise details, it seems clear that the child acquires generative knowledge of his language from limited experience with a part of the whole corpus that is potentially available. Furthermore, on the basis of this limited experience, he is able to extrapolate knowledge about sentences never before experienced by him, as well as knowledge about those never before experienced by anyone.

Presumably, the child's immediate linguistic environment consisting of his or her family and local aspects of his culture, provides him with a generator set of exemplary structures from which he educes the generative principles by which all other sentences are known. Chomsky (1965) has argued that a transformational grammar provides the operations defining the mapping of the generator set of clear case utterances onto the corpus of all utterances; other theorists disagree. However, no one disputes the fact that the acquisition of language requires cognitive schemata that are truly generative in nature.

It is also worth noting that during acquisition specific memory for sentences experienced seems to play no necessary role in the process. Several lines of research support this contention. Sachs (1967) demonstrated that subjects were unable to recognize syntactic changes in sentences that did not change their meaning as readily as they were able to detect changes in meaning. This suggests that people often do not remember the explicit form of sentences experienced. Other researchers (e.g., Blumenthal, 1967; Mehler, 1963; Miller, 1962; Rohrman, 1968) argue that rather than the surface structure of sentences being remembered, it is the deep structural relations specified by current transformational grammars that characterize the abstract conceptual knowledge retained in memory.

One important insight that emerges from a study of such cases is that for generative concepts there are no truly novel instances. There are only those instances that are actual, because they belong to a generator set, and those that are potential, because they lie dormant among the remaining totality of instances. Consequently, the only difference between actual *versus* potential instances is whether the instance has been made manifest by application of the generative principle. Once done so, a newborn instance bears no marks of its recent birth to denote that it is new rather than old.

If the above reasoning is valid, we are able to formulate our first empirical hypothesis: *if people obtain abstract concepts then they will not necessarily be able to recognize novel instances of the concept as being novel; that is, instances in the generator set of a concept (i.e., clear-case exemplars) will not always be distinguishable from those instances never before experienced.*

In the next section we review some of the research recently completed at the University of Minnesota which lends plausibility to the hypothesis that generative systems theory provides a precise description of the function of the cognitive capacity by which we obtain abstract concepts.

EXPERIMENTS ON GENERATIVE CONCEPTUAL SYSTEMS

The problem of how people learn abstract conceptual systems is by no means new to psychology. Sir Fredric Bartlett (1932), in his classic book *Remembering,* realized that what people learn must be some kind of an abstract system or schema rather than a discursive list of simple instances. Clearly concepts can be learned from a small set of very special instances, what might be called *prototypes* or exemplars of the concept. Considerable research has shown this to be the case. However, in doing so some curious results were uncovered. Furthermore, the attempt to characterize precisely the nature of prototypic instances sufficient for the learning of a given concept proved more elusive than expected.

Attneave (1957a) demonstrated that experience with a prototype facilitated paired-associate learning involving other instances of the concept. In related research Posner and Keele (1968) found that subjects were able to classify correctly novel dot patterns as a result of experience with classes to patterns which were abstractly related to the novel instances, i.e., related by statistical rules rather than by feature similarity. Later, Posner and Keele (1970) isolated the following properties of the conceptual systems which enabled subjects to classify novel instances of the classes of dot patterns: (1) this conceptual system was abstracted during initial experience with the classes of patterns, and (2) although derived from experience with patterns, it was not based upon stored copies of the patterns. One week after the original experience with the patterns, the subjects' ability to classify the patterns actually seen earlier had decreased, while their ability to classify "new" prototypic patterns surprisingly had not. This result supports Bartlett's view by strongly suggesting that these "new" instances were classified in terms of a highly integrated system of abstract relations (a conceptual system) rather than being mediated at the time of classification by memory of individual patterns.

The question then is: "how can a subset of instances of a class be used to generate the entire class?" One avenue that we are investigating is to see what insight the concept of group generator may give into the generative nature of conceptual systems.

The notion of a group generator can be understood intuitively by carefully studying the illustrations of the generator and nongenerator sets of stimuli used in the experiment reported below, page 207. One should notice that the *generator* set consists of cards whose relations define the displacements figures undergo when orbiting around the center of the card, that is, when the ordered sequence of cards specifies orbiting. On the other hand, the *nongenerator* set of stimuli consists of cards that are physically similar to those in the generator set, differing, however, in that no sequence of these cards is sufficient to specify the orbiting concept. At most they specify a displacement of four figures over the diagonal path running from the upper left to the lower right hand corners of the card.

In the next section a more formalized account of the group generator notion is presented.

The Concept of Group Generator

Many examples of the generative property of mathematical groups exist. For instance, for each integer n, it is possible to construct a group having exactly n elements (a group of order n) by considering $1, a, a^2, a^3, \ldots, a^{n-1}, a^n$, where $a^0 = a^n = 1$ and the operation is ordinary algebraic multiplication. Such a group is called *cyclic* because the initial element (a^0) is identical to the terminal element (a^n); the symbol a is called a *generator* of the group, since every group element is a power of a, that is, $a \times a = a^2, a \times a^2 = a^3, \ldots, a \times a^{n-1} = a^n = a^0$.

The (integer) representation of the concept of a group with a generator is but one application of this abstract system. As another example, consider the rotational (cyclical) symmetry of a square. Let each vertex of the square be labeled (1, 2, 3, 4,) and represented as the bottom row of a matrix. Then let each position initially occupied by these vertices be similarly labeled and represented in the top row of the same matrix:

$$\begin{array}{ll} \text{positions } (P) & (1\ \ 2\ \ 3\ \ 4) \\ \text{vertices } (V) & (1\ \ 2\ \ 3\ \ 4) \end{array}$$

We now define a 90° clockwise rotation of the square as follows:

$$\begin{pmatrix} 1\,2\,3\,4 \\ 1\,2\,3\,4 \end{pmatrix} \overset{90^\circ}{\Rightarrow} \begin{pmatrix} 1\,2\,3\,4 \\ 4\,1\,2\,3 \end{pmatrix}$$

The 360° rotation of the square can be similarly represented as four 90° rotations:

$$\underset{\text{I}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \end{pmatrix}} \overset{90^\circ}{\rightarrow} \underset{\text{II}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 1 & 2 & 3 \end{pmatrix}} \overset{180^\circ}{\rightarrow} \underset{\text{III}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 4 & 1 & 2 \end{pmatrix}} \overset{270^\circ}{\rightarrow} \underset{\text{IV}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \end{pmatrix}} \overset{360^\circ}{\rightarrow} \underset{\text{I}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \end{pmatrix}}$$

The configurations I–IV are the group elements representing all the possible configurations of a square that can be generated by a product of 90° rotations. This can be summarized in tabular form as follows:

X	I	II	III	IV
I	I	II	III	IV
II	II	III	IV	I
III	III	IV	I	II
IV	IV	I	II	III

From inspection of the table it is clear that I is the identity element and that every element has an inverse, e.g., II × IV = I, III × III = I, etc. To illustrate the group operation, (×), by which these products of rotations in the table above were computed, consider the way in which one proves that the element IV is the inverse of element II since their product II × IV yields the identity element I (a 0° or 360° rotation).

$$\underset{\text{II}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 4 & 1 & 2 & 3 \end{pmatrix}} \times \underset{\text{IV}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \end{pmatrix}} = \underset{\text{I}}{\begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \end{pmatrix}}$$

In general, to multiply one array by another do the following: Replace the value of the vertex in a given position in the first array with the value of the vertex found under the position with the corresponding value in the second array. For instance, in the above example, II × IV = I, the products are computed as follows: V_4 in P_1 of II is replaced by V_1 in P_4 of IV; V_1 in P_2 of II is replaced by V_2 in P_1 of IV, etc., where V_i and P_i denote the appropriate vertex and position.

More importantly (for our purposes), the group of rotations for the square has two generators, namely II and IV. Either of these, if multiplied iteratively by itself, yields all elements of the group. Thus, $\text{II}^2 = \text{III}, \text{II}^3 = \text{IV}, \text{II}^4 = \text{I}, \text{II}^5 = \text{II}$ and similarly, IV^n yields III, II, I, IV, respectively. This generative property is not trivial since neither I nor III are generators of the group; $\text{I}^n = \text{I}$ since it is the identity and III^n alternates between I and III, never producing II or IV because III is its own inverse. Many other groups have nontrivial generators. A most important group is that of perspectives of solid objects. The fact that, for many objects, a few perspectives provide sufficient information to specify their total shape suggests a way in which perceptual systems, like conceptual ones, may be generative. (Shaw, McIntyre, & Mace, 1974)

The basic strategy for testing the applicability of the group-generator description in explaining generative conceptual systems is to construct acquisition sets which either are or are not generators specifying the total class of instances referred to by the concept. This suggests the following hypothesis:

> *If the information specified in the group generator acquisition set is sufficient to allow subjects to generate the entire class, subjects should then treat novel instances of the class in a fashion similar to the way they treat experienced instances of the class. In contrast, the subjects who are given a non-generator acquisition set should treat experienced and new instances of the class differently.*

A Generative Concept Experiment

To investigate the above hypothesis Wilson, Wellman, and Shaw constructed a system consisting of four, simple geometric figures (a *cross*, a *heart*, a *circle*, and a *square*) orbiting alone through the four corner positions of a square card. This allows for the construction of sixteen distinct stimuli (i.e., four figures X four positions = 16 cards). These sixteen cards provide the underlying set over which the concept of *orbiting* can be defined by an appropriate ordering of the cards. Moreover, the system of relationships among the cards determined by the discrete orbiting of the figures, logically specify a group of transformations (displacements) that is isomorphic with the geometric group of 90° rotations of the square discussed earlier. By definition two specific groups (e.g., the *orbiting* and *rotation* groups denoted above) are abstractly equivalent if some third group can be found to represent each. The numeric arrays, I–V with the operation X, constitute such a group.

The sixteen cards which provide the underlying set for the "orbiting" group can be represented by the numeric arrays I–IV as follows: let the top row of the array specify the corner positions on a stimulus card while the bottom row specifies the figures that occur in those positions. In this fashion, the columns of the arrays I–IV, reading from left to right, denote all sixteen cards in the set underlying the concept of orbiting. In the rotation case, each relationship between adjacent arrays specifies the new positions assumed by the vertices of the square as it rotates discretely through 90°; by contrast, in the orbiting case, the relationship between adjacent arrays now provides a summary of the new positions assumed by each of the orbiting figures from card to card. In other words, the orbiting of a figure can be thought of as a rotation around an axis point outside the figure. Hence they have the same group multiplication table and are abstractly equivalent.

The sequence of cards specifying a generator for the 16-card set used in the acquisition phase of the experiment for one group of subjects is shown in Fig. 1.

Notice that the first four cards constitute the columns of array I while the second four cards constitute the columns of array II. To see that these eight

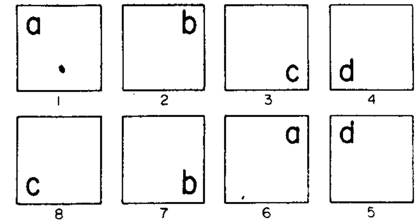

FIG. 1 Group generator acquisition set.

cards qualify as a generator for the total set of cards one need only multiply them together in the iterative fashion as discussed earlier. By consulting the group multiplication table one immediately verifies that multiplying array II (or IV) by itself a sufficient number of times yields all the arrays, I–IV, and therefore, is a generator for the total set of cards. Also by consulting the table, one can verify that iterative multiplication of array III by itself yields only I and III and, therefore, does not qualify as a generator for the group of sixteen cards.

There is a sense, however, in which III is a generator that specifies an abstract concept; namely, since the geometric figures occur in all four positions across cards, if they are treated equivalently, then they do specify the entire set. In order to minimize the *degree of abstraction* (i.e., generality) of the nongenerator acquisition set, eight cards were selected in which the figures occurred in only two positions, rather than four positions specified by III. This selection guaranteed that the nongenerator acquisition set could not specify the entire concept (set) at any level of abstraction. (Although it does contain the generator for a system of diagonal relationships.) The cards in this new nongenerator acquisition set used in the experiment are shown in Fig. 2.

During recognition both groups were shown the eight cards they had experienced during acquisition *plus* the remaining eight novel instances of the system. Additionally, both groups were shown nine cards which did not fit the system, that is, noncases. The noncases were constructed by using inappropriately colored geometric forms, forms occurring in the center of the card, and forms which were oriented differently on the card than those in the system, for example, a 45° rotation from the perpendicular. The recognition set, therefore, consisted of 25 cards, 8 "old" cards, 8 "new" but appropriate cards and 9 "noncases." Subjects were shown each of the 25 cards one at a time and asked

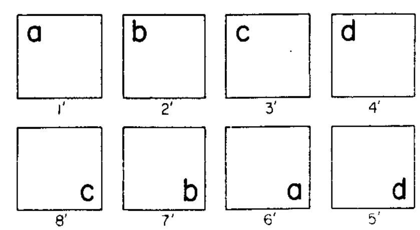

FIG. 2 Nongenerator acquisition set.

to rate each card as "old" or "new," that is, as one they had seen during acquisition.

As might be expected both groups consistently rated the old items as old and identified the noncases as new cards. The generator acquisition set subjects rated old cards as old on 80% of the cases and the noncases as new on 99% of the cases.

The two groups were strikingly different, however, in their judgments of the new but "appropriate within-the-system" cards. The "nongroup generator" subjects correctly identified these new instances as new on more than 90% of the cases. In marked contrast, the "group generator" subjects rated the new cards as being old 50% of the time. That is, their judgments of the new but appropriate instances were at a chance level. On 50% of their judgments, subjects identified the novel instances of the system as cards which they had experienced during acquisition. This group could clearly discriminate system from nonsystem cards, as shown by their rejection of the noncases; but they could not consistently discriminate experienced instances of the system from novel ones.

Two conclusions can be drawn from these results:

1. During acquisition subjects are acquiring information about the abstract relations existing between the items in the acquisition set. That is, they are gaining more information than can be characterized by copies of the individual cards they experienced.

2. The information specified by the group generator is sufficient to allow subjects to generate the entire system. This supports the claim that these subjects' knowledge of the system of orbiting cards is indeed generative.

The fact that subjects in the generator group could not consistently discriminate between previously experienced and novel instances of the system, strongly suggests that subjects are acquiring an abstract relational concept which defines a class of events, not simply information about the specific instances they had experienced. Furthermore, this result also suggests that these subjects acquired a knowledge of an event (the orbiting of cards) that is truly generative. (More about this type of event conception will be said in the next section.)

Assuming that subjects are acquiring abstract relational systems from experience with the generator acquisition set rather than specific memory of experienced instances, the question arises as to the effect of more experience with the acquisition set. Conceptions of memory based upon the abstraction of static features, or copies of the experience events, would predict that more experience with the acquisition set would facilitate subjects' recognition of new instances of the system as actually new, that is, as not before experienced. If, instead of storing copies of the experienced instances or abstracting the common attributes of the instances, subjects are acquiring information about the abstract relations among these instances in the system, more experience with the acquisition set would not necessarily result in an increased ability to recognize new instances of the system as being novel. As subjects better acquire the abstract relational

system they would be more able to discriminate instances of the system as being novel. As subjects better acquire the abstract relational system they would be more able to discriminate instances of the concept from noncases. However, the novel instances of the system may be more difficult to discriminate as new precisely because they are instances of an abstract relational system

To investigate this possibility, four additional groups were run, two with each of the two types of acquisition sets. One group experienced the generator acquisition set twice, and a second group three times. Similarly, a third experienced the nongenerator acquisition set twice and the fourth group experienced it three times. Following the acquisition phase, all groups were tested for recognition.

In the nongenerator groups, the greater amount of experience with the acquisition set resulted in an increased ability to recognize the new instances of the system as new. The subjects who experienced the acquisition set three times were able to recognize the new instances as new on 100% of the cases. The nongenerator subjects were able to consistently identify new instances of the concept as new after one presentation of the acquisition set, and the subjects given more experience with the nongenerator acquisition were even more accurate in this discrimination. However, the results obtained with subjects who experienced the group-generator acquisition set were quite different. Not only were these subjects unable to identify novel instances of the system as new, but additional experience with the acquisition set decreased the subjects' ability to recognize new instances as being new. As stated earlier, the subjects who experienced the acquisition once accepted the new instances as old 50% of the time. Subjects who experienced the acquisition set twice before recognition identified the new instances as old on 75% of their judgments, and the subjects who experienced the generator acquisition set three times identified the new but appropriate instances of the system as old on over 80% of their judgments. All of these subjects continued to correctly recognize the old instances as old and reject the noncases as not before experienced.

These results provide strong evidence that subjects are acquiring information about an abstract system of relations and not simply information about the static properties or attributes of the experienced instances. If subjects' judgments were based solely upon the attributes or static features of the experienced instances, the subjects would be able to recognize new but appropriate instances as being new and increase experience should enhance this recognition. As we have seen the results were not obtained. On the other hand, if subjects are acquiring a generative conceptual system, then, instances which are appropriate to the system would be recognized as familiar. As the abstract conceptual system is better learned the subjects' would be more likely to recognize novel instances of the system as belonging to the system and, therefore, identify them as old.

It should be noted that these data provide strong support for our hypothesis, namely, that knowledge of a subset of the instances of a concept was in fact tantamount to knowledge of all instances of the concept. When the system was well learned, subjects could not distinguish old from novel instances. Clearly, experience with the group-generator acquisition set was in this case tantamount to experience with the entire system.

Finally, it should be noted that in these experiments subjects were *not* instructed to find relations between the individual instances, nor were they told that they would be tested for recognition. Rather, subjects were instructed that we were studying short-term memory of geometric forms. Their task was to reproduce, by drawing each card in the appropriate acquisition set after performing an interfering task. In this case, the abstraction of the systematic relations between instances of the system appears to be automatic in the sense that it was not intentional.

EVENT CONCEPTS AS GENERATIVE KNOWLEDGE

In this section we present evidence in support of the contention that event concepts are abstract in nature and therefore generative.

Shaw, McIntyre, and Mace (1974) argue that perceiving the nature of events involved the detection of sufficient information to specify their *affordance* structure. The term "affordance" is borrowed from James Gibson (1966) and refers to the invariant perceptual information made available by objects and events that specifies how animals and humans might adapt to their environments.

The affordance structure of events consists of two necessary components: the transformation over which the event is defined (the transformational invariant) and the structures which undergo the change wrought by the application of the transformation (the structural invariant). The transformational invariant must be perceptually specified in the acquisition set if the dynamic aspects of the event are to be identified (e.g., that the event is of x running, rolling, growing, smiling, etc.), while the structural invariant must be perceptually specified if the subject of the event is to be identified (e.g., what x is: *John* runs, the *ball* rolls, the *flower* grows, *Mary* smiles, etc.).[1] A set of instances of an event is not an exemplary set and, therefore, does not constitute a generator set for the event, if it fails to provide perceptual information sufficient to specify both the transformational and structural invariants. To summarize this hypothesis:

> *All necessary conditions being satisfied, a person will acquire the concept of an event when presented with an acquisition set of exemplary instances (a generator set) because such a set provides the minimal perceptual information sufficient to specify the affordance structure of the event.*

In the experiment discussed in the previous section we showed how a certain subset of object configurations qualified both formally and psychologically as the generator set for an event concept, that of an "orbiting" event defined over geometric forms. Thus, the group generator description does seem to offer a viable means of making explicit the manner in which abstract conceptual systems may be creative.

The abstract concept derived from perceiving the orbiting of the stimulus figures can be analyzed as follows: The generator set in the acquisition phase of the experiment consisted of stimulus configurations sufficient to specify a subgroup of the displacement group, namely, the orbiting group. This set of stimuli constituted the structural invariant of the event while the group operation (orbiting) constituted the transformational invariant of the event. The subjects succeeded in obtaining the concept of this event by detecting these two invariants which taken together constitute the affordance structure of the event.

The orbiting group itself provides a description of the relevant aspects of the abstract concept of the event. Thus construed, the perceived meaning of the event *is* the orbiting group interpreted over the stimulus structures presented. Consequently, we see no way or reason to avoid the conclusion that in all event perception situations the existence of an abstract concept is entailed. Under this view, the generator for the abstract event concept is that set of instances which conveys sufficient perceptual information to specify both the transformational and structural invariants defining the event. The meaning of this invariant information for the human or animal perceiver is the affordance structure of the event.

In our opinion, this analysis argues in favor of the hypothesis that perception is a direct apprehension of the meaning of events insofar as their affordance structure is concerned. Since abstract concepts are generatively specified by (i.e., abstractly equivalent to) their exemplary instances (generator set), their acquisition can also be considered direct, requiring no augmentation by voluntary inferential processes. Similarly, no constructive cognitive process need be postulated to explain how abstract concepts are built up out of elementary constituents as argued by the British Empiricists since such elementary constituents play no necessary role in the definition of the concept.

Have we made too much of the apparent success of the generative systems approach in a single line of experiments? It is important to ask whether the same

[1] Perhaps a better way to clarify the difference between structural and transformational invariants is as follows: given that John runs, John walks, John smiles, John loves, the subject of all these events is John; the subject's structure is what is common or invariant and, hence, is the *structural* invariant of all the events denoted. On the other hand, given the following events: John runs, Bill runs, Mary runs, Jill runs, then there is no common subject. All we know is that some object with a minimal structure to support the operation *to run* is involved. The operation on the minimal structure x is the transformational invariant. But note that even here to define that transformation presupposes some minimal structural invariant as its necessary support. A similar argument for the necessity of postulating minimal transformational invariants in order to define structures can also be given. For these reasons the affordance structure of events, inclusive of actions and objects, necessarily requires both structural and transformational invariants for its definition. Since in ecological science there are only affordance structures, that is, animal–environment, or subject–object relations, the affordance concept is a universal semantic primitive that deserves careful study by cognitive psychologists.

analysis can be applied to a variety of experimental phenomena. We explore this possibility in the next section.

Perceiving the Affordance Structure of Elaborate Events

So far we have presented an example involving an event whose affordance structure can be formally described by very simple group structures, i.e., orbiting. We would now like to discuss two complex events whose affordance structures, although more elaborate, still seem amenable to generative systems theory.

The shape of nonrigid objects. Theories of object perception usually attempt to explain the perception of objects and patterns which do not change their shape over time. However, a truly adequate theory must also explain the origin of concepts of events where object configurations or the shape of objects undergo dynamic change. Shaw and Pittenger (*in press*) have conducted a series of experiments designed to explore this problem The assumption behind the research is this:

Shape is considered to be an event-dependent concept rather than an absolute property of static objects. This is contrary to the traditional view that identifies shape with the metric-Euclidean property of *geometric rigidity under transformation,* that is, the fact that under certain transformations (e.g., displacements) the distances between points on an object do not change. Unfortunately, this definition is too narrow since it fails to apply to a manifold of natural objects which remain identifiable in spite of being remodeled to some extent by various "nonrigid" transformations (e.g., growth, erosion, plastic deformation under pressure).

Biomorphic forms, such as faces, plants, bodies of animals, cells, leaves, noses, inevitably undergo structural remodeling as they grow, although their transforms retain sufficient structural similarity to be identified. Such forms, like geological structures under plastic deformation or archaeological artifacts under erosion, are relatively nonrigid under their respective remodeling transformations. Since the property of geometric rigidity is not preserved by any of these, it cannot provide the invariant information for their identification. Clearly, then, a new and more abstract definition of shape must be found upon which to develop a theory of object perception that is broad enough in scope to encompass all objects—rigid as well as nonrigid ones. Consequently, the following definition was decided upon: *Shape, as an event-perception concept, is to be formally construed to mean the sum total of invariant structural properties by which an object might be identified under a specified set of transformations.*

This definition should sound familiar since it is but a restricted version of the definition of the affordance structure of objects given earlier. But notice, that by this definition the geometric rigidity of an object under displacement is but one

of the many kinds of structural invariants possible. By a careful study of the perceptual information used to identify human faces at different stages of growth (i.e., age levels), it was hoped that the generality and fruitfulness of the event-perception hypothesis might be further tested.

Perceiving the shape of faces as a growth event. Faces, no less than squares or other shapes are dynamic events since their affordance structure (e.g., shape) is derived from a growth process (the transformational invariant) which preserves sufficient structure (structural invariant) to specify the identity of the face of the person undergoing the aging transformation (growth). In a similar fashion, different people at the same stage of growth, can be perceived as being at the same age level because growth produces similar effects over different structures (Pittenger & Shaw, 1975). These common effects constitute the information specifying the transformational invariant of the growth process. Thus, each transformation can be identified by the style of change wrought over various objects to which it is applied.

In addition to empirically discovering the invariant information specifying the identity of the structures over which an event is defined, a problem of equal weight for the event perception hypothesis is to isolate the invariant information specifying the transformation by which the dynamic aspect of an event is defined. Both of these informational invariants must be found in every event perception experiment if the affordance structure of the event being studied is to be experimentally defined. Pittenger and Shaw conducted the following experiments in an attempt to discover the affordance structure of the growth event defined over human faces. The biological literature suggests two classes of transformations for the specification of the transformation of skull growth: strain and shear. A strain is a geometric transformation which, when applied to a two-dimensional coordinate space, changes the length of the units along one axis as a transformation of the units along the other axis. For instance, a strain transformation can take a square into a rectangle or vice versa. On the other hand, a *shear* is a geometric transformation which transforms the angle of intersection of the coordinate axis, say from a right angle to something less or more than a right angle. Such a transformation might take a square into a rhombus. Consequently, Pittenger and Shaw constructed a set of stimuli by having a computer apply different degrees of these two transformations to a human facial profile, and then by photographing the computer plotted transforms of the given profile. Three experiments were run to test the hypothesis that the perception of age level is derived from information made available by growth events.

To illustrate the application of these transformations to faces, we will describe the production of stimuli for the first experiment. The stimuli were produced by applying combinations of these transformations globally to a two-dimensional Cartesian space in which the profile of a 10-year-old boy had been placed so that the origin was at the ear hole and the y axis was perpendicular to the Frankfurt horizontal (a line drawn tangent to the top orb of the ear hole and the bottom orb of the eye socket).

The formula used for the shear transformation in producing the stimuli expressed in rectangular coordinates was $y' = y$, $x' = x + \tan \theta y$, where the $\tan \theta$ is the angle of shear and x', y' are new coordinates. The formula for the strain transformation used, expressed for convenience in polar coordinates, was $\theta' = \theta$, $r' = r(1 - k \sin \theta)$, where r is the radial vector and θ is the angle specifying direction from the origin. Here k is a constant determining the parameter value of the strain. Thus in producing the stimuli $\tan \theta$ and k are the values to be manipulated for varying the amount of shear and strain, respectively. (For a detailed discussion of this approach see Shaw & Pittenger, in press.) The calculations were performed by computer and the profiles drawn by a computer-driven plotter.

The initial outline profile was transformed by all 35 combinations of seven levels of strain ($k = -0.25, -0.10, 0, +0.10, +0.25, +0.35, +0.55$) and five levels shear ($\theta = -15°, -5°, 0°, +5°, +15°$). These transformations are not commutative. Shear was applied first. The resulting profiles are shown in Fig. 3.

These shape changes approximate those produced by growth. We hypothesize that the changes are relevant to perception in two ways; they are a sufficient stimulus for the perception of age while at the same time leaving information for the identity of the face invariant. The reader will note, however, that profiles on the extreme values for each variable are quite distorted. These values were

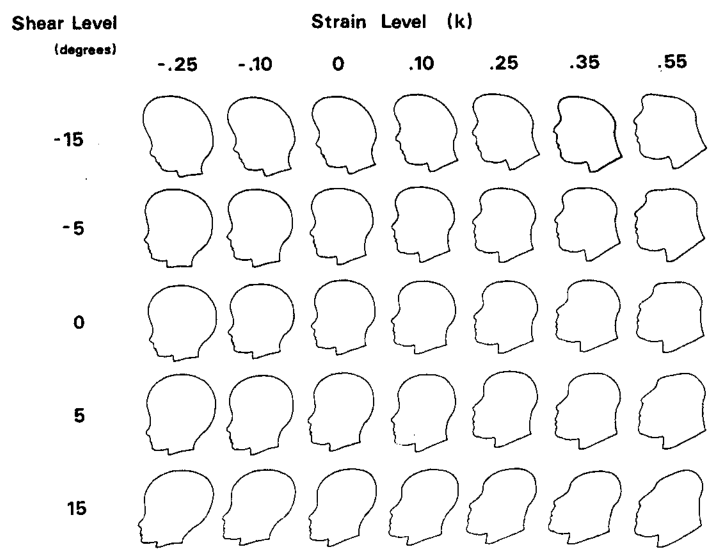

FIG. 3 Transformation of a facial profile by shear and strain.

chosen to test the supernormal stimuli hypothesis. Supernormal stimuli are produced by exaggerating some relevant aspects of a stimulus. Ethologists claim that such stimuli lead to exaggerated responses (Tinbergen, 1951).

Experiment 1

To test the effects of the shape changes induced by shear and strain the profiles shown in Fig. 1 were presented by slide projector to the subjects in a task requiring magnitude estimates of age. The subjects were instructed to rate the ages of the profiles by choosing an arbitrary number to represent the age of the first profile and assigning multiples of this number to represent the age of succeeding profiles relative to the age of the first. Twenty subjects were asked to rate the 35 slides resulting from the transformations described above. The results were straightforward. Using a Monte Carlo technique Pittenger and Shaw found that 91% of the judgments made by the subjects agreed with the hypotheses that the strain transformation produced monotonic perceived age changes in the standard profile. On the other hand, using the shear transformation to predict judgments produced only 66% agreement. Since strain was by far the strongest variable of age change, we decided to test the sensitivity of subjects to very small changes in profiles due to this transformation.

Experiment 2

Sensitivity to the shape changes produced by the strain transformation was assessed in the second experiment by presenting pairs of profiles produced by different levels of the transformation and requiring subjects to choose the older profile in each pair. A series of profiles was produced by applying strain transformations ranging from $k = -0.25$ to $+0.55$ to a single profile, where k is the coefficient of strain used in the equation controlling the computer plots. Eighteen pairs of profiles were chosen; three for each of six levels of difference in degree of strain. The pairs were presented twice to four groups of ten subjects. Different random orders were used for each presentation and each group. Subjects were informed that the study concerned the ability to make fine discriminations of age and that for each pair they were to choose the profile which appeared to be older. During the experiment they were not informed whether or not their responses were correct. By correct response we mean the choice of the profile with the larger degree of strain as the older.

Several results were found. An analysis of variance on percentage of errors as a function of difference in strain showed a typical psychophysical result—a decline in accuracy with smaller physical differences and an increase in sensitivity with experience in the task. However, two other aspects of the results are more important for the question at hand. First, subjects do not merely discriminate the pairs consistently but choose the profile with the larger strain as the older profile with greater than chance frequency; in the first presentation the larger strain was selected on 83.2% of the trials and the second, on 89.2% of the trials. In each presentation, each of the 40 subjects selected the profile with the larger k as older on more than 50% of the trials. In other words, the predicted effect was obtained in every subject. A sign test showed the change probability of this last result to be far less than .001. Thus, the conclusion of the first experiment is confirmed in a different experimental task. Second, sensitivity to the variable proved to be surprisingly fine.

Experiment 3

A third experiment was designed to determine if a structural invariant existed by which individual identity might be perceived as follows. We have all had the experience of recognizing someone we know as a child years later when they have grown to maturity. As a preliminary test of preservation of identity under the strain transformation, profile views of the external portions of the brain cases of six different skulls were traced from x-ray photographs and subjected to five levels of strain. Five pairs of transformed profiles were selected from each individual sequence; the degree of strain for members of three pairs differed by 0.30 and those of the other two pairs by .45 values of k. A profile of a different skull was assigned to each of the above pairs which had the same degree of strain as one of the members of the pair. Slides were constructed of the profile triples such that the two profiles from distinct skulls which had the same level of strain appeared in random positions at the bottom. Thirty subjects were presented the slides and asked to select which of the two profiles at the bottom of the slide that appeared most similar to the profile at the top. The overall percentage of errors was low: for the 30 sets of stimuli presented to 30 subjects, the mean error was less than 17%, with no subject making more than 33% errors. Since no subject made 50% or more errors, a sign test on the hypothesis of chance responding (binomial distribution) by each subject yields a probability of far less than 0.001. Indeed, in another set of studies, Pittenger and Shaw also found that people are quite able to rank order by age photographs of people taken over nearly a decade of growth from pre- to post-puberty years.

The results of these three studies provide support for two important hypotheses: the strain transformation due presumably to growth, not only provides the major source of the relevant perceptual information for age level, but also leaves invariant sufficient perceptual information for the specification of the individual identity of the person by the shape of the head alone.

These experiments also support the contention that the perceived shape of an object is not simply the shape of a static, rigid object, but is rather a higher order structural invariant which remains relatively unchanged by the events (i.e., transformational invariants) into which such objects may enter. Further dramatic support for this claim is provided by the fact that the identity of human faces is preserved under elastic transformations as distinctive from growth as artistic characterization. The success of political caricaturists rests on their ability to satirize a political figure by exaggerating distinctive body or facial features without obscuring the identity of the famous or infamous personage depicted. Indeed, there is evidence that such an artistic redition of complex structures facilitates their indentification (Ryan and Schwartz, 1956). But will the event perception hypothesis apply equally well to still more elaborate events in which complex transformations are defined over a variety of structures?

Perception of a tea-making event. Recently, at the Center for Research in Human Learning, Jerry Wald and James Jenkins have been investigating the generative nature of an elaborate event: the act of preparing tea. To study this event 24 photographs were taken depicting the various steps involved in the preparation of tea. These stimuli were presented to subjects following the same experimental design used in the "orbiting" event experiment discussed earlier. Sixteen of these 24 pictures were used as an acquisition set portraying the tea-making event to subjects. Later, these 16 pictures, plus the remaining 8 from the original set, were shown to the subjects, who were asked to indicate whether the picture was new or one which occurred during acquisition. The subjects were unable to distinguish the new but appropriate pictures of the event from the pictures they had actually experienced during acquisition. Once again we see that a partial subset of the possible instances of an event can specify the entire event.

The general results found in this experiment were essentially the same as those found in the case of the "orbiting"-event experiment reported earlier. Namely, it was again found that subjects were very good at recognizing as new pictures which were physically similar to those in the acquisition set but inappropriate as elements in the event. For example, if a type of movement or direction of movement inappropriate to the event portrayed during acquisition was depicted, subjects classified the picture as new. Clearly, the knowledge which subjects gained during acquisition was knowledge of an abstract system of relations, that is, an event, not knowledge of exact copies of the exemplars specifying the event. Additional support for the contention that subjects are acquiring a generative system of relations is provided by the finding that subjects who were provided more experience with the acquisition pictures were even more likely to mistake the novel but appropriate instances for those actually seen.

GENERAL CONCLUSIONS, AND IMPLICATIONS FOR INSTRUCTION

Each of the event perception experiments discussed is not only amenable to a generative systems explanation but seems to require it. The range of events surveyed, from simple events such as orbiting objects, to more elaborate events involving growth of human faces and the preparation of tea, suggests that the ability to formulate abstract concepts is a basic cognitive capacity underlying knowledge acquisition. This characterization of knowledge acquisition has several important implications for a theory of instruction.

The most general implication concerns how we should conceptualize the nature of those situations in which we accrue useful knowledge about our natural, cultural, social, and professional environments. If the majority of our experiences in these areas involve encounters with either novel instances of old events or fresh instances of new events, then the goals on instruction must go beyond concern for how particulars may be learned. Rather, the primary goal should be to train people to exploit more efficiently their cognitive capacity to assimilate knowledge that is abstract and, therefore, generative.

Moreover, if adaptive responding to even ordinary events, such as recognizing faces or making tea, entails generative knowledge of abstract relationships, then this is all the more true for dealing with higher forms of knowledge in such fields as science, philosophy, mathematics, art, history, or law. Acquisition of knowledge in all areas is a result of abstraction over well chosen instances of events, the exemplars which instantiate the generator sets for the concepts involved. Accepting these conclusions, what potential impact might such a cognitive theory of knowledge have upon current educational practices?

1. Programs of instruction should primarily consist of lessons in which students are furnished with direct experience with those core concepts of the field. As we saw in the case of the experiments reported, the abstraction of generative systems requires first-hand experiences with those exemplary instances of a concept that constitute its generator set. However, our educational institutions typically, and sometimes exclusively, use the "lecture" technique by which students are made passive recipients of the conclusions or implications drawn from another person's experience, where in actuality some version of the experience itself would be a much better form of instruction. Instruction, which takes the form of learning facts or principles about some concept x, is not a substitute (although it may be a useful supplement) for acquiring direct experience about concept x, even if presented in some analogical or simpler prototypical form. This is why some courses of study wisely rely heavily upon laboratory or field experience. Indeed, every classroom should be a "laboratory" for first-hand, rather than second-hand experiences.

There is little new in the above observations regarding the preference of active participation in the learning process over passive reception of material to be learned. What is new, however, is the insight that the generative capacity to formulate abstract concepts may be naturally engaged when the student experiences a very special subset of exemplars, namely, the generator. Therefore, the selection of the exemplars of a concept to be taught is a very different affair, requiring the joint efforts of cognitive psychologists and instructional experts.

2. Another, related implication of the generative characterization of conceptual knowledge is to offer a new theory of the transfer of training effects so desirable throughout the educational progress of a student. How do old concepts facilitate the learning of new ones; and how does new information become integrated with existing information?

Since the generative nature of knowledge has not been seen as implying a core cognitive capacity, both specific and general transfer have been seen as a secondary, spin-off effect of learning specific reactions to specific objects or events. We have attempted to show throughout this chapter why this characterization of learning is backwards. The generative cognitive capacity that is responsible for transfer is not derivative from or based upon knowledge of exact replicas or copies of experiences. It is the abstractness of concepts that accounts for the generality or transfer of conceptual knowledge gained in one situation to new situations. Transfer, therefore, is inherent in the acquisition of abstract concepts.

3. A final implication of this theory for instruction related to the selection of criteria for evaluating performance as an indicant of the state of conceptual knowledge attained by the student. This has proven to be a most difficult and, somewhat surprisingly, a most controversial issue. The proposed theory suggests why this is so.

A major source of difficulty in the evaluation of the knowledge a student has acquired is to know what types of performance count. There are several performance levels students may attain due to either their sophistication in an area, their motivation, or the nature of the concepts to be learned. First, and easiest to evaluate, is the ability to verbalize, or articulate in some other overtly demonstrable form, exactly what they know about a topic. Unfortunately, this level of performance is exhibited inadequately by most people and tends to be rare except for simplistic cases where a rote memorization of particulars is appropriate. Such knowledge, however, is not necessarily generative in nature and, thus, its successful evaluation poses no guidelines for an adequate evaluation of students' abilities to use abstract conceptual knowledge.

A second and more frequently exhibited performance level is that the student has attained useful knowledge of a topic but is unable to articulate what he or she knows. Clearly, a very important goal of education is to bring a novice in some subject matter area up to the level of an expert. Indeed, often we would be very happy if our pedagogical attempts had even more limited success in that the student somehow learned to make sound judgments although remaining unable to articulate the basis for the judgments.

This state of affairs, rather than being rare among experts, is actually very common. Few experts can specify, in algorithmic clarity, the reasoning process they go through in order to arrive at a sound judgment with respect to a problem in their area of expertise, although they may present a learned rationalization afterwards. Many art connoisseirs are able to distinguish styles of artists, categorize according to era, culture or school, various artifacts presented to them without being able to say beforehand the criteria they use. Similarly, chess masters intuit outcomes of games and strategies of opponents without being able to specify a priori criteria for doing so. Indeed, in all areas of knowledge, to be an expert is synonymous with the ability to render objectively sound judgments without necessarily being able to specify every step in the ratiocinative process involved. If it were not so difficult to do so, educating novices to the level of experts would only require rote memorization of algorithmic judgmental procedures applied to rotely memorized banks of data.

The intuitive judgments of experts do, of course, promulgate from a knowledge basis, but one that is usually more tacit than explicit. In short, expert judgments are a by-product of generative systems of knowledge rather than of inert data banks of factual information. Consequently, in our effort to evaluate how much closer to an expert's judgmental ability education has moved novices, we want to assess primarily the degree of generative, tacit knowledge they have obtained and not just their explicit knowledge of itemized facts. Based on the current theory and findings, we suggest that the following questions should be answered by any knowledge evaluation procedure:

a. Can the student identify the same set of clear-cases of the concept that a majority of experts agree upon? This includes also the ability to distinguish non-cases from true cases.

b. Will the student, once tutored in the concept area, select a prototypical instance of the concept from a recognition set of instances as being most likely an instance previously studied, even though it was, in fact, never seen?

c. Can the student deal with novel instances of the concept with the same facility shown with familiar ones? And corollary to both (b) and (c):

d. Does the repeatedly tutored student display an inability to recall whether he or she has seen relevant particulars about the concept area before, while at the same exhibiting considerable confidence that irrelevant particulars were not seen before? This is a very important criterion for determining if the student has indeed built up tacit knowledge structures that are not accessible to conscious articulation. In fact, the proportion of false positives in recognition tests may provide the only way to determine whether an inarticulate student has nevertheless gained sufficient knowledge for making sound intuitive judgments (on the assumption, of course, that a comparison of the students' judgments with that of experts is not directly feasible).

Obviously, there is still much work to be accomplished before drawing any final conclusions about the proposed theory. It already exhibits, however, in our opinion, sufficient promise in both theoretical and practical areas to merit further development by both cognitive and educational psychologists.

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