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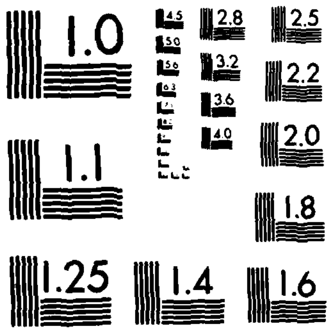

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A FRAMEWORK FOR FORMING, MODIFYING, AND USING MULTIMEDIA CONCEPTS IN MEMORY

Part I: Mathematical Formulation

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A theoretical framework for the structures and processes of memory is presented. The model is based on three main notions: memory, concepts, and processors. Part I puts forth the notions in mathematical terms. (Part II will give an interpretati in psychological terms.)

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) "is a subconcept of." At a given time, each concept has a set of locations assigned to it. The assignment is made by an allocation function. A state of memory is defined as a set of concepts, the relation "is a subconcept of," an allocation function, and an evaluation function.

Processors change the state of memory and provide interaction with the environment (input/output). Each processor operates with a limited number of concepts at a given time. The action of a processor is determined by concepts, mainly by the values of locations allocated to a given concept and by the input stimulus from the environment. For a given processor, the concepts which determine the action of the processor will be called the executable concepts for the processor.

We assume that locations are of three categories: data, instructions, and pointers. Data locations contain values that are an encoding of basic sensory stimuli, such as auditory and visual input. Instruction locations contain values that are executable by a processor. Pointer locations have values that point to another concept, thereby providing linkage between concepts. We assume that a single concept generally contains locations of different categories, for example, encoded data from visual and auditory stimuli, executable motoric values, and pointers.

We define what it means for one concept to be a generalization of another, and for one to be an abstraction of another. We also define an inversion operation, in which concepts map to subconcepts and subconcepts map to concepts. It seems to have an important role in linguistic processing.

Examples are given for clarification.

A Framework for Forming, Modifying, and Using

Multimedia Concepts in Memory

Part I: Mathematical Formulation

Part II: Psychological Interpretations

Abstract for Part I

A theoretical framework for the structures and processes of memory is presented. The model is based on three main notions: memory, concepts, and processors. Part I puts forth the notions in mathematical terms. (Part II will give an interpretation in psychological terms.)

Memory is viewed as a set of locations, and locations have values. An evaluation function attaches a value to a location. The basic unit in memory is the concept. Concepts have a hierarchical structure. They are related by the relation "is a subconcept of." At a given time, each concept has a set of locations assigned to it. The assignment is made by an allocation function. A state of memory is defined as a set of concepts, the relation "is a subconcept of," an allocation function, and an evaluation function.

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Examples are given for clarification.

A Framework for Forming, Modifying, and Using Multimedia Concepts in Memory

Part I: Mathematical Formulation

Introduction

This paper attempts to present a framework within which one can analyze behavior. The behavior is based on stimuli coming from different media, such as auditory, visual, and others, and includes responses which are not necessarily verbal, but, for example, motoric, etc. The basic notion is that of a <u>concept</u>. A concept is a chunk of information which is processed as a unit. This definition is slightly circular. When we are asked how one knows that a given chunk of information is a concept, we answer, because it is processed as a unit.

Concepts are assumed to be multimedia. This means that information that is put together into a concept comes from different sources, for example, visual and auditory. It also means that a concept contains other information such as motoric information. An example of motoric information is information about how to move one's hand.

<u>Processors</u> are assumed to create and use concepts. We hypothesize that there is one processor, which we call <u>central</u>, whose main task is to modify concepts. These concepts are to be used by other processors.

We assume that concepts are stored in memory, and that memory can be viewed as a two level structure. On one level are locations where information can be stored, and on the other is the actual information which is stored in the locations.

The relationship between concepts and memory is assumed to be as follows: At a given time, a concept is assigned a set of locations in memory, where the chunk of information is actually stored. This assignment is assumed to be dynamic. Namely, at different times, the same concept can have different locations assigned to it, and also the information stored in those locations can vary.

The paper presents a mathematical formulation of this model using elementary set theory and expressing the notions in terms of sets, functions, etc. Assumptions are formulated in terms of propositions about some basic notions and in terms of propositions about other notions defined in terms of the basic ones.

In part one of the paper (presented here) we use examples for clarification of the notions. The main examples used are either abstract or based on analogy. For example, a chess board can be viewed as a memory in which information, namely, a position in a chess game, is stored.

In part two of the paper (Note 1) we re-examine some standard psychological notions, such as learning, language acquisition, forming associations between visual and verbal stimuli, etc., within the framework presented above.

The leitmotif of the paper is the following: Thinking is processing concepts. But concepts are far from being linguistic objects, e.g., word concepts. Linguistic elements can be part of concepts, but they are not at all necessary for thinking. Processes such as generalization and abstraction can be carried out without any linguistic elements. We view the processes mentioned above as very basic processes of thinking, and we view their connection with linguistic elements as more accidental, due to the way that they are communicated between individuals.

I. Basic notions

In this section some basic notions are presented. They are primitives, i.e., they are not defined.

A. Locations; Memory as a set of locations; Value of a location; Evaluation function.

The question "What is memory?", can be answered in two ways. First, memory can be viewed as a physical object or a set of physical objects. That is, it can be viewed as a set of locations. For example, the peripheral memory in a computer might consist of two disk packs. The memory in an organism is located in the nervous system.

As an analogy, a chess board can be considered a memory. It consists of 64 squares or locations. Similarly, a Monopoly board can be considered a memory. It consists of spaces, or locations, where pieces can land, where houses and hotels are placed, where cards are put, and where money is kept.

Second, memory can be viewed as having a content, or value for each location. In this paper, memory is viewed as having locations, and locations are viewed as having values. For example, in a calculator, there may be a register x (a location) that can have as content a number (a value). In the chess board example, each square (location) can have a value. For a given position, the values of the locations are the pieces on the squares. We assume that the value of a location can be undefined. An undefined value can mean many things. One example is when we don't know which value is there. Another example is when the absence of a piece is interpreted to mean that the value is undefined.

In this paper, memory is viewed as a set L, called locations, and a set V, called values. In order to be able to say that every location has a value, we will assume that there exists a selected element $u \in V$ such that having a value u means that the value is undefined.

The next basic notion is that of an evaluation function. It is a mapping E which attaches a value $v \in V$ to a location $x \in L$. Thus E: L--->V.

We illustrate the idea of an evaluation function with a chess board example. Figure 1 shows a chess board laid out at the beginning of a game.

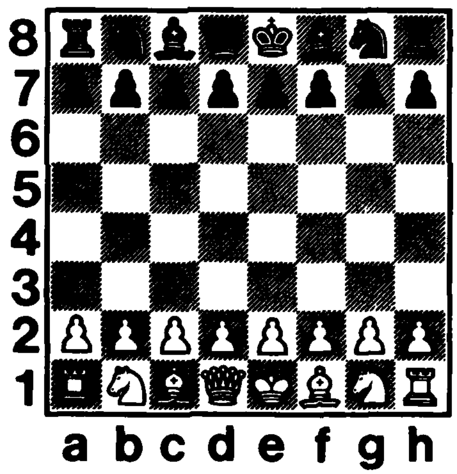

Figure 1. A chess board laid out at the beginning of a game. The rows and columns are numbered and lettered according to algebraic notation.

The rows and columns are numbered and lettered according to algebraic notation. At the beginning of a game, location b1 on the board holds a white knight, and location h8 holds a black rook. This situation is expressed as E(b1)=white knight, and E(h8)=black rook. In this case, b1 and h8 are the names of locations (elements of L), and white knight and black rook are the names of values (elements of V).

B. Concept; Allocation Function; Relations between Concepts; and Relations between sets of Locations.

Following Leibniz (see Loemker, 1956), a basic unit in memory is the <u>concept</u>. (Leibniz' term was <u>monad</u>.) At a particular time, a concept has a set of locations assigned to it. (The same concept can have different sets of locations assigned to it at different times.) Using the chess board analogy, a concept could be the black squares, and the set of black squares would be the set of locations assigned to it (in this case, permanently). Another concept could be the squares occupied by pawns. Here, the set of locations assigned to the concept would vary during the chess game.

The mapping of concepts into sets of locations is given by an <u>allocation function</u> A, which attaches to a concept a set of locations. Let us denote by C the set of all possible concepts. An allocation function A is a function from a finite subset K of C into subsets of L. We denote it as A: K---> subset (L).

We assume that there is a relation between concepts: "is a subconcept of." It is a partial ordering relation. For two concepts C_1 and C_2, if C_2 is a subconcept of C_1, we write C_2 sub C_1. For example, the concept of black pawns will be treated as a subconcept of the concept of black pieces.

We can define another relation between concepts, namely, the inclusion relation between sets of locations allocated to concepts. For the concepts C_1 and C_2 it can be written $A(C_2) \subseteq A(C_1)$.

We assume C_2 sub C_1 implies $A(C_2) \subseteq (C_1)$, but not necessarily vice versa. The locations occupied by black pawns always form a subset of the locations occupied by black pieces. But, on the other hand, if in a given position all black pawns are sitting on white squares, this does not imply that the concept black pawns is a subconcept of the concept white squares.

C. Categories of locations

We assume that there are three basic categories of locations: data locations, instruction locations, and pointer locations.

Data locations contain values that are an encoding of basic sensory stimuli. Subcategories of data locations can be, for example, auditory locations and visual locations. Subcategories are divided into types. A type location can be thought of as a container of a particular size and shape. It is made to hold only certain values, and not others. Types of visual locations, can be, for example, color locations, size locations, shape locations, etc. So, for example, a color location would have as a value an encoding of redness.

Instruction locations contain values that are executable by a processor. For example, a location on a Monopoly board can contain a card which reads, "Go directly to jail." Instruction locations are divided into two subcategories, input/output and central.

Types of input/output hold input/output instructions, such as instructions which direct movement (for example, sneeze, move the left hand, chew), and attentional instructions (such as listen to or ignore a noise, or find out what color something is). Values of locations of type central are, for example, create a concept, generalize a concept, allocate or disallocate locations, form associations, etc.

Pointer locations contain as values addresses of concepts. An address of a concept is a value which gives direct access to the concept. Therefore, if A(C) contains a pointer location which has as a value the address of a concept C', we can consider that the concept C' is linked to the concept C. Pointers are analogous to semantic network links (Anderson and Bower, 1973; Collins and Loftus, 1975; Norman and Rumelhart, 1975). When a pointer is followed, a concept is reached. A pointer has a type. The type tells which class of concept (see IV below) is pointed to.

II. A state of memory, a notion defined in terms of the basic ones.

A state of memory consists of a set of concepts, the relation "is a subconcept of" (sub), an allocation function A, which allocates to each concept a set of locations, and an evaluation function E, which gives some specific value to each location.

We give an example of a state of memory using a chess board. Consider the set K of concepts {black squares, white squares, black pieces, black pawns, white pieces}. Consider memory to be tne 64 squares (locations) on the board:

a1, a2,....., a8

.

.

.

.

h1, h2,....., h8.

(These are labeled in Figure 1.) Let the set of values be all the pieces on the board, plus the empty square (with no piece). Suppose there is one relation, "is a subconcept of", between two concepts, as follows:

{black pawns} sub {black pieces}

The configuration that we are about to describe is shown in Figure 2.

Let the allocation function A assign locations to concepts as follows:

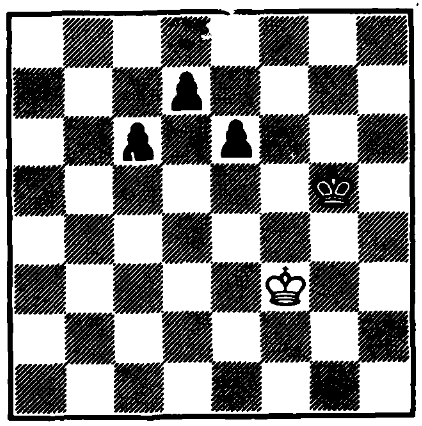

Figure 2. A chess board configuration described in the text.

A (black squares) = {a1,a3,a5,....}

A (white squares) = {b2,b4,b6,...}

A (black pieces) = {c6,d7,e6,g5}

A (black pawns) = {c6,d7,e6}

A (white pieces) = {f3}

Examples of values assigned by the evaluation function E are:

E(e6) = black pawn

E(e7) = empty (or undefined)

E(f3) = white king

E(g5) = black king

It is also the case that

A (black pawns) $\subseteq$ A (white squares), and

A (white pieces) $\subseteq$ A (white squares).

But it is not the case that {black pawns} sub {white squares}, and it is not the case that {white pieces} sub {white squares}.

III. More basic notions: Input and output signals, and a processor and its operation.

Two more basic notions are input (I) and output (O) signals. Among other things, input signals can include verbal instructions, and output signals can include actions. One action, for example, is speaking.

A processor, another basic notion, is a partial function from a state of memory and some input into a state of memory and possibly some output. It changes the state of memory and provides interaction with the environment (input/output).

The basic operation performed by a processor (i.e., the action of a processor) is to take some number of arguments, which are concepts, and in addition an input signal. It produces a new sequence of concepts, and perhaps an output signal. Practically, what this means is that the concepts which are used as arguments can be modified, and some output signal can be created.

Each processor operates with a limited number of concepts at a given time. The action of a processor is determined mainly by the values of locations allocated to some given concept(s) and by the input signal from the environment.

We illustrate the notion of a processor and how it changes the state of memory with two examples. We start with the configuration shown in Figure 2. Suppose the input signal I is a verbal instruction, the output O is an utterance, and the processor P is a person who moves a piece on the chess board according to the instruction. The input is, "Move a black pawn to d5." The processor takes as arguments the concept black pawn and the instruction, "Move a black pawn to d5." It changes memory from state one to state two. The concepts, allocation function, and values for state one are given above, in the description of Figure 2. The following changes are made:

State 1	------------->	State 2
E(d7) = black pawn		E(d7) = empty

E(d5) = empty	E(d5) = black pawn
*d7 $\in$ A(black pawns)	d7 $\notin$ A(black pawns)
**d5 $\notin$ A(black pawns)	d5 $\in$ A(black pawns)

* is an example of deallocation of a location.

** is an example of allocation of a location.

The configuration for state two is shown in Figure 3.

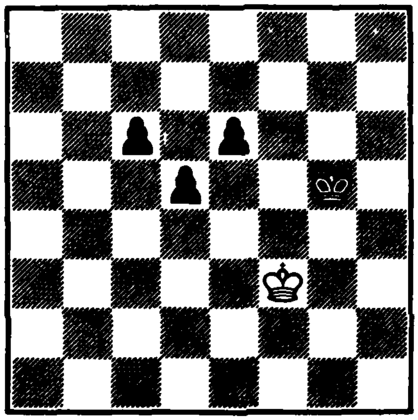

Figure 3. Another chess board configuration described in the text.

Notice that the concepts in states one and two are the same. P did not produce any new concepts. It just changed the allocation function and value for two locations. After changing the state of memory, P says, "I did it." This is P's output signal.

Assume the next input signal is, "Now consider the kings." P wants to create a new concept, i.e., the concept of {kings}. P takes as arguments the black pieces and the white pieces, and the input signal, and creates kings. It thereby changes memory from state 2 to state 3. It allocates to the concept locations f3 and g5. In state two there were the following concepts: {black squares, white squares, black pieces, black pawns, white pieces}. State three has the concepts {black squares, white squares, black pieces, black pawns, white pieces, kings}. In addition, the allocation function A (kings) = {f3,g5}. The allocation functions for the other concepts do not change, and the value functions also do not change. P says, "Okay, what should I do now?" This is P's output signal.

Using the chess analogy, we have shown examples of how the state of memory changes from one to two to three, what happens to allocation and evaluation functions, and how a new concept is created and an output signal produced.

We hypothesize that there are two kinds of processors, central and input/output. We further hypothesize that there is only one central processor, and its main task is to modify concepts or form new ones. The primary task of input/output processors is to provide interaction with the environment.

How many input/output processors there are, and exactly what their duties are, we are not ready to specify. But we suppose that, for example, in the visual cortex there is an input/output processor which builds images. That is, it provides concepts with visual components. It takes signals from the retina and gives values to locations.

Similarly we suppose that in the auditory cortex there is an input/output processor which provides concepts with auditory components. It takes signals from the basilar membrane and gives values to locations in the form, for example, of "loud noise."

The part of the brain which controls movement of the right hand can be localized. That part of the brain, we hypothesize, is an input/output processor. The processor takes the concept "raise the right hand" and transforms it into a set of signals. When the signals are sent to the peripheral nervous system, they will make the right hand rise. Also, the processor creates a concept which contains a memory for the movement performed.

We think that there exists a linguistic processor which is separated from the auditory and the visual one. Linguistic abilities are not lost with a loss of hearing or with a loss of vision. This indicates that linguistic processing is done by some special processor. We return to linguistic processing in part VI below.

IV. Classes of concepts

Concepts are divided into classes. There are concepts which are executable by the central processor and concepts which are executable by input and output processors. This is the key point for classification: The fact that a concept is in a particular class gives information about which processors can use it and how the concept is used.

We are not ready to specify all the possible classes of concepts. But a concept in the class _object_ might contain as a subconcept a concept in the class _sensory_ which can be operated on only by input processors. A concept in the class _action_ might have a concept in the class _motoric_ as a subconcept, which only an output processor can try to execute. A concept in the class _abstract_ might have the property that no input or output processors will try to execute it; only the central processor will attempt execution. The notion of executing a concept will be expanded on in the next section.

We also hypothesize that there are concepts in the class _linguistic_. They will be discussed in VI.

V. Notions defined in terms of other notions

We first introduce some terminology. For a concept C, S(C) will denote the set of all subconcepts of C, including C itself.

Suppose there are two concepts, C and C'. A mapping f from C to C' is a function which has domain S(C) U A(C), such that f(S(C)) sub S(C'), and f(A(C)) $\subseteq$ A(C'). (A is an allocation function, which attaches to a concept a set of locations.) In other words, the mapping takes subconcepts into subconcepts, and locations into locations.

Property 1. A mapping f is structure preserving if it satisfies the following three conditions:

a) If C_1 and C_2 are elements of S(C), and C_1 sub C_2, then f(C_1) sub f(C_2).

b) If C_1 is an element of S(C), and x is an element of A(C_1), then f(x) is an element of A(f(C_1)).

c) If x is an element of A(C) and is of category pointer, and if the value of x points to C_1 which is an element of S(C), then f(x) is a pointer whose value points to f(C_1).

Property 2. A mapping f is type preserving if it satisfies the following two conditions:

a) If C_1 is an element of S(C), then class (C_1) = class (f(C_1)).

b) If x is an element of A(C), then category (x) = category (f(x)).

Property 3. A mapping f is value preserving if it satisfies the following condition: If x is an element of A(C), then value (x) = value (f(x)).

Property 4. A mapping f is partial value preserving if it satisfies the following condition: If x is an element of A(C), then either value (x) = value (f(x)), or value (f(x)) is undefined.

Using these four properties, we can define some relations between concepts.

A. Sameness (isomorphism) of concepts.

Definition. Given two concepts C and C', we say that C is isomorphic to C' if there exists a one-to-one mapping f: C ---> C', such that both f and its inverse f^{-1} satisfy properties 1, 2, and 3 (f is structure, type and value preserving).

We give an example. Suppose in memory there are locations of different types. Suppose that, among other types, there are type letter, whose values are letters of the alphabet, and type digit, whose values are the nonnegative integers 0, 1,..., 9. We denote a location for type letter by an open square and a location for type digit by an open triangle.

Suppose there are three concepts, C_1, C_2, and C_3. The situation is shown in Figure 4.

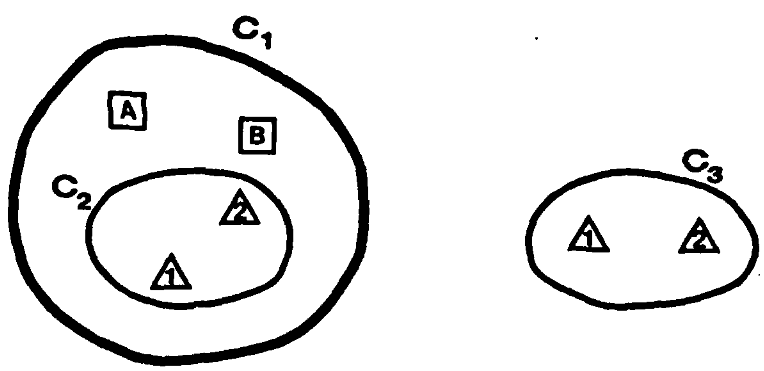

Figure 4. Concepts C_2 and C_3 are isomorphic.

Assume C_2 is a subconcept of C_1. (This is the only relation among the three that we assume.) Let the allocation function attach to C_1 four locations, two of type letter and two of type digit. Let the value function attach to the two letter locations the values A and B, and to the two digit locations the values 1 and 2. Let C_2 be a subconcept of C_1 consisting of locations containing digits.

Let the allocation function attach to C_3 two locations of type digit, and let the value function attach to them the digits 1 and 2. Then C_2 and C_3 are isomorphic.

The two concepts shown in Figure 5 are also isomorphic. Notice that pointers pointing outside do not have to point to the same concept, or even to isomorphic concepts. They must point to concepts of the same class (see IV above), however.

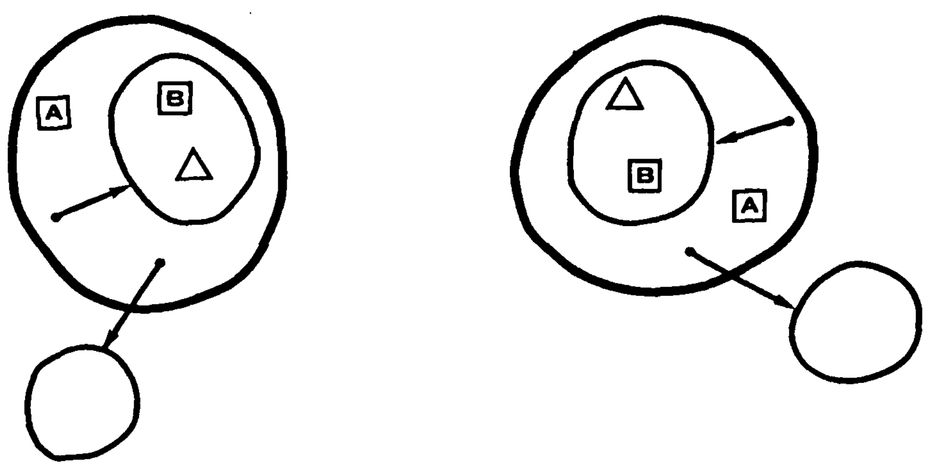

Figure 5. The two concepts shown are isomorphic.

In I.B. we noted that C_2 sub C_1 implies $A(C_2) \subseteq A(C_1)$, but not necessarily vice versa. We illustrate this by an example. Suppose there are concepts C_1, C_2, C_3, and C_4, as shown in Figure 6. The only relation assumed is that C_2 is a subconcept of C_1; C_4 is <u>not</u> a subconcept of C_3. It happened incidentally that the same locations (those containing the values A and B on the

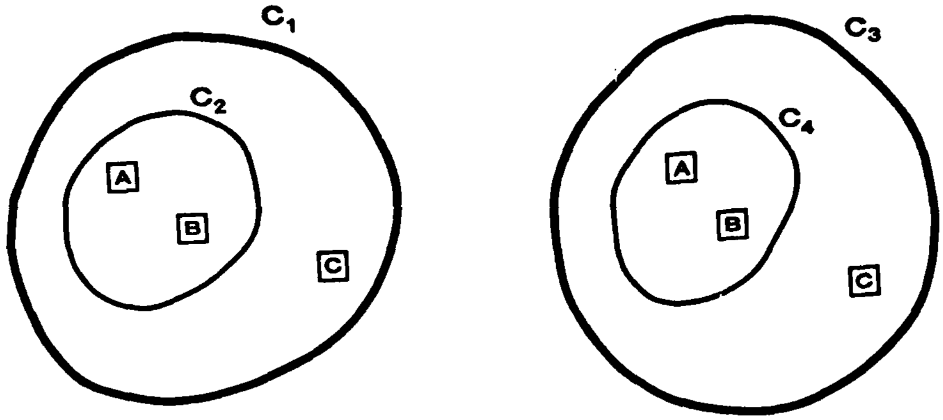

Figure 6. C_2 is a subconcept of C_1, but C_4 is not a subconcept of C_3. (See text for an explanation.)

right of Figure 6) were allocated to different concepts. Here, then, it is not true that C_4 sub C_3. But it is true that $A(C_4) \subseteq A(C_3)$. One can therefore allocate new locations to C_4 (and not to C_3), thereby breaking the allocation inclusion. Such a state of affairs is shown in Figure 7.

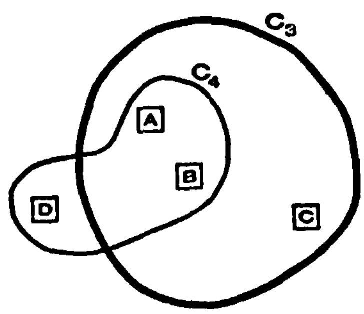

Figure 7. A new location, containing the value D, has been allocated to concept C_4 and not to concept C_3. This can happen because C_4 is not a subconcept of C_3.

Notice the trivial case. Suppose there are two concepts C_1 and C_2, such that $A(C_1) = A(C_2) = \emptyset$, the empty set. It is not necessarily the case that C_1 and C_2 are identical.

We have two forms of identification of concepts, one strong and one weak.

<u>Definition</u>. Two concepts C_1 and C_2 are identical (strong form) if and only if C_1 sub C_2 and C_1 sub C_1. (It follows that $A(C_1) = A(C_2)$.)

<u>Definition</u>. Two concepts C_1 and C_2 are identical (weak form) if and only if $A(C_1) = A(C_2)$.

If two concepts are identical (strong form), it means that the locations allocated to them are always the same. Weak form identity means only that at a given time the allocated locations happen to be the same.

B. Generalization

<u>Definition</u>. We say that concept C' is a generalization of concept C (or C' is more general than C) if there exists a one-to-one mapping, f: C--->C', that satisfies properties 1, 2, and 4 above (i.e., f is structure preserving, type preserving, and partial value preserving).

An example is shown in Figure 8. There, concept C' is more general than concept C.

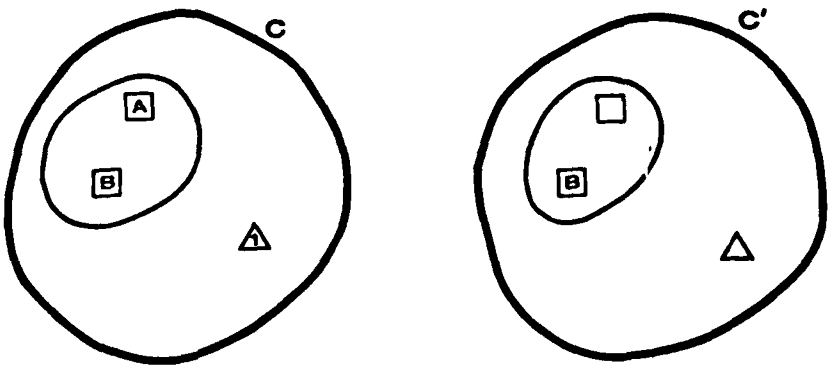

Figure 8. Concept C' is more general than concept C. (Conversely, concept C is more specific than concept C'.)

We call the inverting (f^{-1}) of generalization specification. Concept C is more specific than concept C'.

C. Abstraction

Definition. We say that concept C is an abstraction of concept C' (or C is more abstract than C') if there exists a one-to-one, not necessarily onto, mapping f from C into C' which satisfies properties 1, 2, and 3 above (i.e., f is structure, type, and value preserving).

An example is shown in Figure 9. In it, concept C' is more abstract than concept C. We call the inverting (f^{-1}) of abstraction concretization. Concept C is more concrete than concept C'.

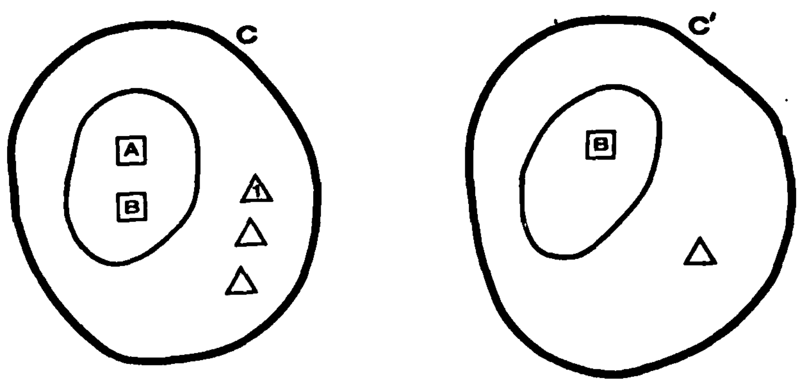

Figure 9. Concept C' is more abstract than concept C. (Conversely, concept C is more concrete than concept C'.)

D. Copy and edit

Now we can define operations on concepts. Intuitively, they are operations that some processors can perform on a state of memory.

<u>Definition</u>: To copy concept C means to construct a new concept C' which is isomorphic to C.

<u>Definition</u>: To generalize C means to change some values in A(C) from defined to undefined.

<u>Definition</u>: To abstract C means to remove some subconcepts from C and some locations from A(C).

Compositions of generalization, abstraction, specification, and concretization will be called <u>editing operations</u>.

We assume that the main role of the central processing unit is to perform the following function: to copy and edit concepts.

In talking about processing, we need to specify what it means to learn to generalize. In our framework, it means creating a concept that can be executed by the central processing unit, which results in the creation of generalizations.

For example, imagine the following situation. Suppose one wants to create a generalization of color. One has a concept for creating the generalization of color. It is concept G in Figure 10. Concept S is some concept to be generalized. (In Figure 10 and some others that follow, a schematic notation is used to represent informally the internal structure of a concept. Concepts are represented by circles. Locations are represented by rectangles. And values are represented by words put in brackets. For example, <red> represents some encoding of the stimulus red.)

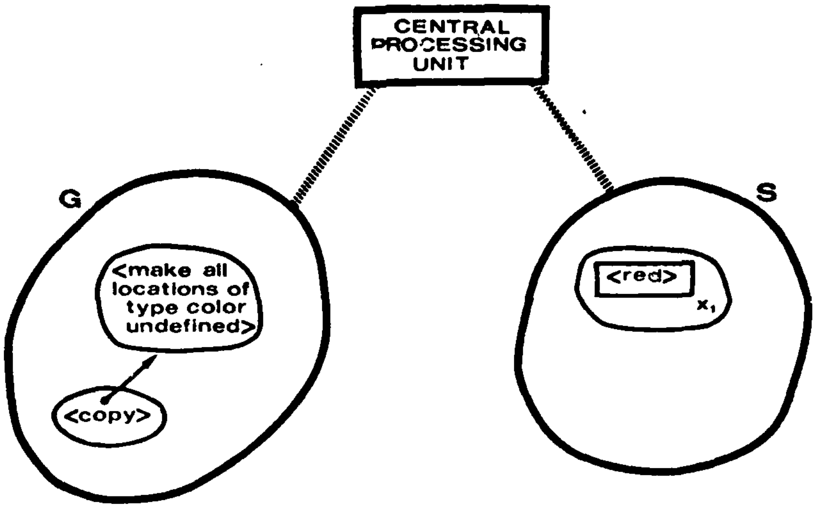

Figure 10. When concept G is executed, it creates the generalization of color. Concept S is some concept to be generalized. It has a location, x_1, of type color, with value <red>.

For simplicity, let us say that the central processing unit (CPU) operates on two concepts at a time. When G is built, the CPU makes a copy of S and generalizes it. The result of the generalization is a concept that is identical in structure to concept S (in Figure 10), but which has the value <red> removed from the rectangular box. So the color becomes undefined.

This brings up an important point. After G is created, it is not necessary to have more than one instance of color in order to make a generalization. The commonly accepted mechanisms of generalizing or abstracting from several instances (e.g., Rosch and Lloyd, 1978; Smith and Medin, 1981) are only a special case of the mechanism hypothesized here. It is popularly assumed that in order to have a generalization, one has to have a variety. For example, in order to create a concept of a flower ι <u>any</u> color, one needs concepts of flowers of at least two different colors.

Using our terminology, this special case of the process of generalizing from two or more instances is viewed as follows:

We take a group of concepts which are structurally identical, i.e., between any two there is a mapping which satisfies property 1 above. We create a new concept, structurally identical to the previous ones, which is a generalization of all the compared concepts. The value for a location in the new concept is made undefined if the corresponding values are not identical in all concepts.

As stated above, we view this as a valid mechanism for generalization, but we do not assume that it is the only one. In our framework, the process of generalization via making values undefined can be done on the basis of only one case.

For example, suppose one sees some new object, perhaps a new animal. One does not have to see another one to imagine it a different color (i.e., to change the value of its color). This ability is probably connected with transfer of learning. One learns in one situation and can use what is learned in others.

Similarly, one popular way to view the process of abstraction is as follows. From a group of concepts, one creates a concept that is an abstraction of all compared concepts. Again, within our framework, one can construct an abstraction from just one example.

Still on the topic of abstraction, we give here a possible hypothetical conceptual representation of the number five. We suppose it may be a concept which has no locations assigned to it, but which has five subconcepts in the class object, as shown in Figure 11.

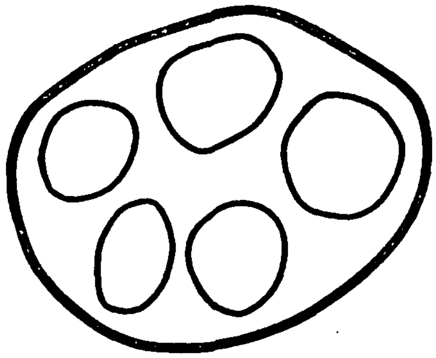

Figure 11. A hypothetical conceptual representation of the number 5: A concept with no locations, but with five subconcepts in the class object.

Now, what would it mean to answer, "How many?" We assume one takes a concept and makes the following abstraction. One removes all locations and removes all subconcepts that are not in the class object, leaving only those in the class object. One removes all subconcepts of subconcepts in the class object.

If the person wants to say the word five, he or she makes a match of the concept resulting from the above editing operations to another concept which is exactly like that in Figure 11, except that it contains one extra executable subconcept that is the linguistic element "five". We hypothesize that this is the way objects are counted.

We assume that abstraction satisfies properties 1, 2, and 3 above (structure, type, and value preserving). However, if one considers a higher level abstraction, that is only structure and value preserving, and not type preserving, one can count things other than objects. In the procedure to count, one could remove all locations and all subconcepts except those of a given class. For example, one could remove all subconcepts except those in the class movement (or action).

One could be asked, for example, how many things do you have to do to bake a cake? The person can answer: There are six steps. Why six, and not 20, one might ask. The reason is, hypothetically, that the person has a concept of baking a cake, and the person applies the specific algorithm above to it (removing locations and all subconcepts except those in the class action), and what is left is six. The operation of counting actions as legitimate as the operation of counting sheep.

Two points need to be emphasized. First, we assume that an algorithm for abstraction (the process of abstraction) is itself a concept which, when executed together with other concepts by the central processor, yields an abstract version of the other concepts. In a manner similar to generalization, it is possible that this algorithmic abstraction concept is built as a generalization of many special cases of abstraction. But we do not exclude the possibility that this concept can be built on the basis of just one example, or even without any example at all.

The second point to be emphasized is that whether or not the result of abstraction is objective on the physical level is irrelevant. It does not matter whether there are really six steps in baking a cake. The executable concept of abstraction operates on a concept of baking a cake, and not on the activity in the kitchen. The result of six steps can be interpreted as follows: The person's concept of baking a cake has six subconcepts of class action.

Suppose one is asked, how many of everything does a dog have? This is an example of a nonexecutable concept of counting. Why? In counting, we look at only some particular classes of concepts; we remove everything (except some classes). We remove all subconcepts of subconcepts as well, and then we arrive at a number. (For abstract numbers, the matching done is not necessarily class preserving.) To answer the question, How many of everything does a dog have?, requires that one count all the subconcepts of a particular concept. We do not seem to have a procedure (an executable concept) for that.

VI. Inversion

When we considered different mappings between concepts, such as generalization and abstraction, (in V. above), the key point was, which properties of the concept are preserved under the mapping and which can change. In V we defined a structure preserving mapping f between concepts. We review that notion before turning to an inversion mapping.

With a structure preserving mapping, subconcepts are mapped into subconcepts and locations into locations. Figure 12 shows a structure preserving mapping in which

D sub C,

f(C) = C',

f(D) = D',

and therefore D' sub C'.

An inversion mapping

Definition: A mapping f from C to C' is called an inversion mapping if:

f is one-to-one on locations

f is value preserving

f inverts the notion of subconcept. That is, if D sub C, then C' sub D'.

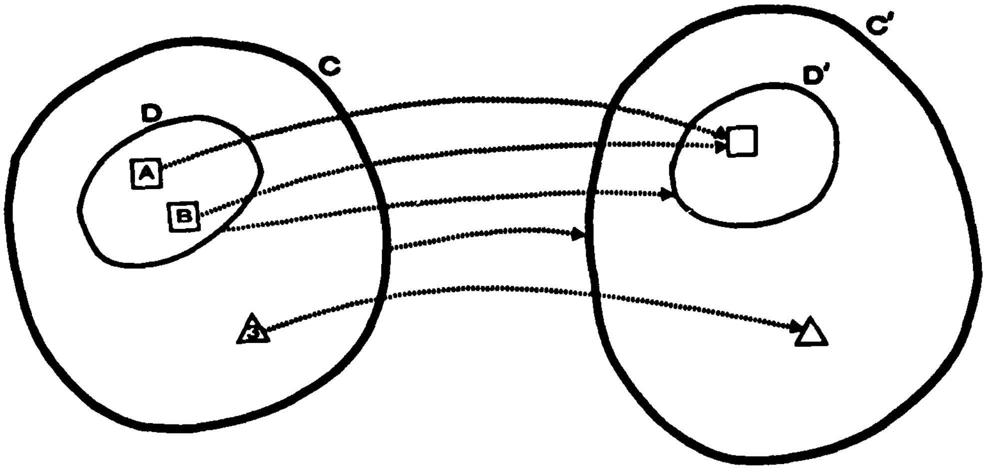

Figure 12. A structure preserving mapping. ---> represents the mapping or function. The structure is preserved: sub is preserved, and type is preserved. The mapping is not 1-1 on locations, and the mapping is not value preserving.

Figure 13 shows an example of an inversion mapping. On the left, D sub C. On the right, C' sub D'.

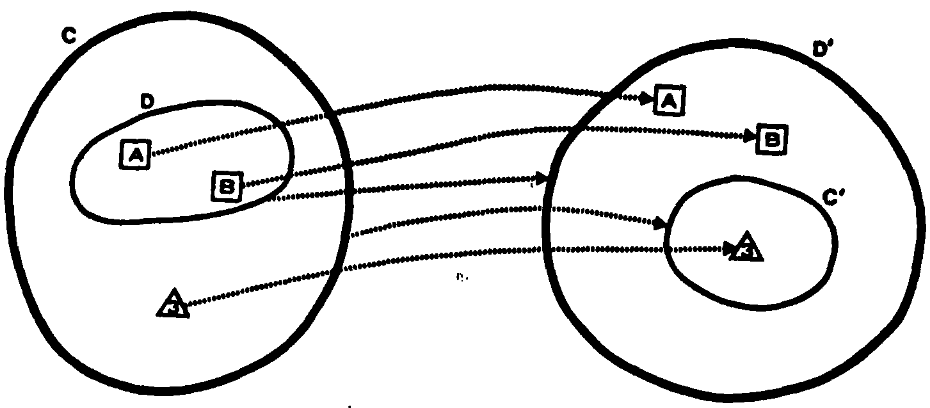

Figure 13. An inversion mapping.

We assume that the process of inversion is the main process in forming concepts in the class linguistic (linguistic concepts). Let us assume in Figure 13 that C is a nonlinguistic concept, let us say, of class object, which contains a linguistic subconcept D. The locations in the linguistic subconcept may contain motoric information (how to articulate some word, for example) and some auditory information (how to recognize some particular word when it is spoken). The motoric information may be executable by the processor that controls the larynx, tongue, and lips. The auditory information may be executable by the processor which controls the auditory system.

The locations in the concept C outside D (such as $\triangle 3$) may contain visual or other sensory information about the object. If the information is visual, it can be of type color, shape, or size, for example.

The inversion produces a concept D' of class linguistic which now contains as a subconcept C' of class object. This inverted concept can be further processed by operations of abstractions and generalizations.

We hypothesize that the inversion mapping is the basic mechanism in language acquisition, in forming abstract linguistic concepts, and in speaking.

We illustrate the hypothesis with an example. Let us suppose that a person has a concept C of class object whose linguistic subconcept D is animal. That the linguistic component is animal means that the person can say, "animal", and can recognize it when it is spoken. This information is represented in D (class linguistic) sub C (class object). The concept C can contain many nonlinguistic elements, for example, visual elements for recognizing a cat, dog, mouse, horse, and bird; motoric elements of petting a cat, olfactory and tactile elements, etc.

Let us create a concept D' by inversion, and abstract it by removing all locations and subconcepts of C' (C' sub D'). Now we arrive at a very abstract linguistic concept of animal: an object called animal, without executable elements of recognizing cats and dogs. The concept D' has the name animal, and it has the subconcept C' of object. A person with this concept knows there is an object called an animal, but his or her concept does not contain any information that allows the person to recognize an animal.

It is possible to make a less drastic abstraction. One could preserve in C' information that the object is alive, for example. A person with such a concept would have information that the object called an animal is alive.

We give one final example of how concepts look in this framework. Suppose there is a concept C with two subconcepts C_1 and C_2. C is of class object, C_1 is of class sensory, and C_2 is of class linguistic. C_1 has three locations, x_1, x_2 , and x_3, of type color, size, and shape, respectively. The locations have values <red>, <small>, and <sphere> respectively. The situation is shown in Figure 14.

The content of C_2 is represented by <ball>. If we looked at C_2 under a microscope, we would see quite a few subconcepts and maybe even a hierarchical structure. There would be auditory and motoric elements, with pointers between them. There might be a hundred locations of different types and categories.

To extend the picture, suppose there is a concept D of class action. It is a concept that can (possibly) be executed by the motoric system. Suppose it appears as in Figure 15. X is type pointer to object, in the category pointer. D_1 is in the class action. This means it is potentially

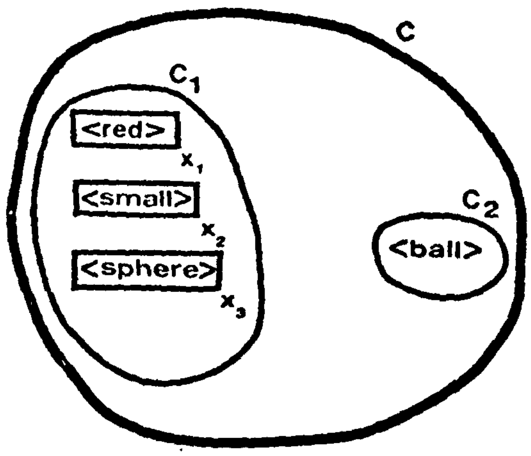

Figure 14. An example of a hypothetical concept C of class object with two subconcepts, C_1 of class sensory and C_2 of class linguistic. Locations x_1, x_2, and x_3, allocated to C_1, are of type color, size, and shape, respectively.

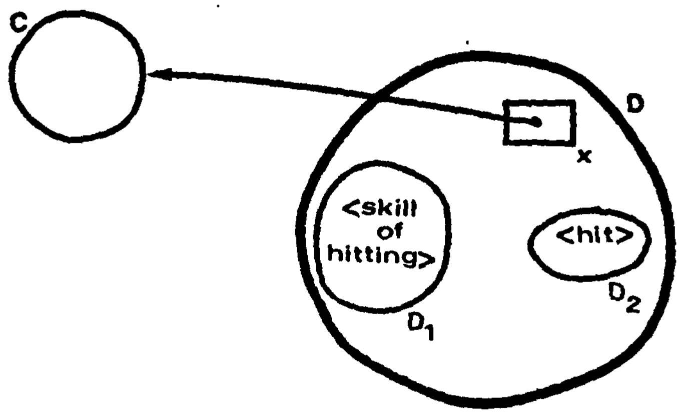

Figure 15. A concept D of class action. It is described in the text.

executable by motoric elements of the peripheral nervous system. D_2 is in the class linguistic (and includes the motoric element for speaking). The value of D_2 is <hit>. The value of D_1 is <skill of hitting>. And the value of x is a pointer to C (the C shown in Figure 14).

A possible scenario in which concepts C and D might occur is as follows. Suppose there is a parent and little Jimmy, age two. Suppose Jimmy has concepts C and D shown in Figures 14 and 15, and suppose there is a small red ball, and he has a stick. The parent throws the ball and says, "Jimmy, hit the ball." Jimmy hits the ball and says, "Hit...ball." What processing is Jimmy doing?

He first matches the auditory stimulus in the parent's utterance with the auditory component of his linguistic subconcepts of his concepts C and D. So the auditory components of <hit> and <ball> can be recognized. Also, he visually can match the ball with sensory elements in C_1: <small>, <red>, and <sphere>. So the visual input is matched with the sensory subconcept C_1.

Next, he attempts to execute the subconcept D_1 of D. (Probably D_1 contains an element that is a pointer to D_2 . Figure 15 is schematic and does not show all the connections.)

After hitting the ball, Jimmy executes the motoric element of the linguistic subconcept D_2. That is, he says the word hit. After that, there is still a pointer from D to C, and Jimmy executes the motoric element of the subconcept C_2. That is, he says the word ball.

Now suppose Jimmy is age five, three years older. His parent says, "Do you recognize this ball? Do you want to play with it?" At age two his linguistic subconcept C of ball might have looked as shown in Figure 16.

His linguistic concept of ball at age 5 might look as shown in Figure 17.

At age two, Jimmy's concept of ball has subconcepts in the class sensory and possibly motoric, and a linguistic subconcept that is auditory and motoric. By age five, he has developed a linguistic concept by inversion.

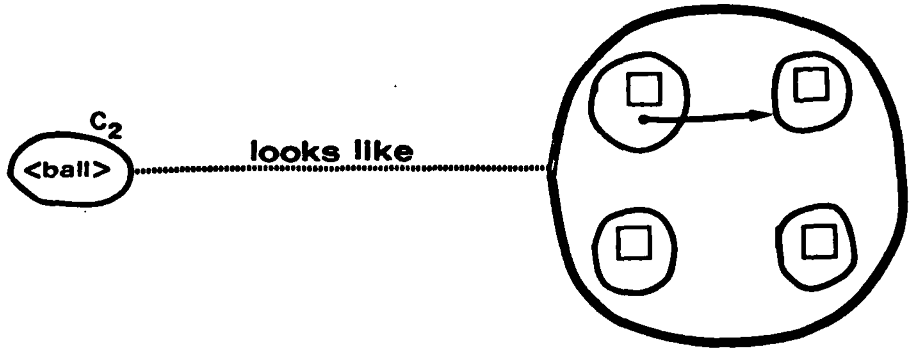

Figure 16. A hypothetical linguistic concept of a two year old child. The subconcepts are sparse and not well connected.

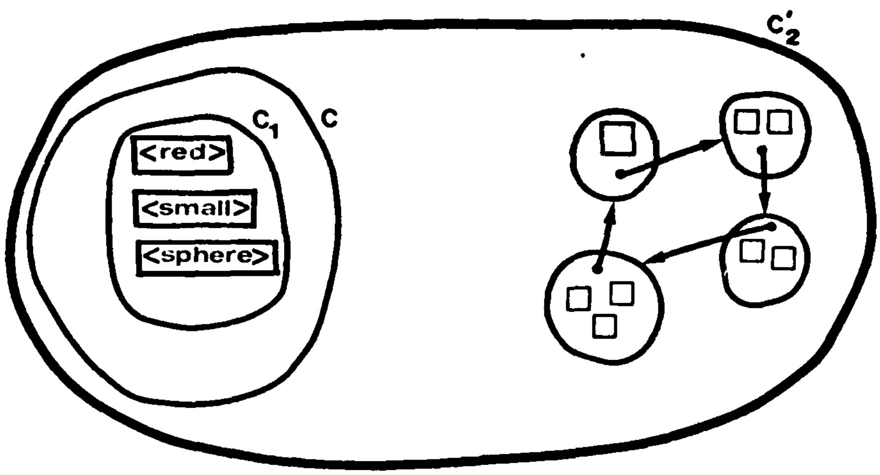

Figure 17. A hypothetical linguistic concept of a five year old child. On the right is a more developed form of C_2 from Figure 16.

What is the reason for forming linguistic concepts? Let us see what happens when one generalizes and abstracts Jimmy's early concept of hitting, the one shown in Figure 15. The result might be waving the hand, with <u>no</u> linguistic component; very likely the linguistic component is lost.

Now let's take Jimmy's linguistic concept of hit, developed later. What is the use of it? Suppose Jimmy as a teenager wants to learn to play blackjack. He hears the terms "stand" and "hit". He thinks, "I know what stand and hit mean, but what do they mean in blackjack?" He takes his abstract linguistic concept of hit and adds a subconcept to it, for scraping cards along the table to indicate one wants another card. This subconcept has motoric elements (how to do it) and visual ones about when to do it. Now Jimmy's linguistic concept hit contains a subconcept of class action. He knows what he should do when playing. He can invert his linguistic concept (with action subconcept) to an action concept when he wants to be hit in blackjack.

We hypothesize that the process described above is the basic one in learning from verbal materials.

Summary and Conclusions

This paper has attempted to present a framework within which one can analyze behavior. Why this particular one? It is on the one hand very complex. But if any of the notions is omitted, a big gap occurs in our ability to interpret behavioral phenomena; some we simply cannot interpret at all.

On the other hand, within the framework we seem to be able at least to formulate most, if not all, of the questions asked about human (and, importantly, nonhuman) thinking. (See Note 1.)

Taking another perspective, the framework is very simple. It postulates that all thinking is processing concepts. And the concepts are processed according to the simple rules of creating, copying, and editing. The complexity comes from the fact that concepts are built from information coming from very many sources: visual, auditory, kinesthetic, and so on. But the processing of concepts is uniform. Abstraction, generalization, and inversion can be performed on any concept.

The biggest departure of this framework from current views is that the ability for abstract thinking does not preassume the capacity for language. The prerequisites for abstract thinking seem to be only abstraction, generalization, and inversion. The fact that we invert mainly relative to linguistic concepts seems to be rather incidental.

Footnote

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Reference Note

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