Project Address:

IBM Deutschland GmbH
WT LILOG / Dept. 3504
P. O. Box 80 08 80
D-7000 Stuttgart 80
Fed. Rep. of Germany

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On Structuring Domain-Specific Knowledge

Ipke Wachsmuth

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Author's address: IBM Deutschland GmbH, LILOG / Dept. 3504
P. O. Box 80 08 80, D-7000 Stuttgart 80, Fed. Rep. of Germany

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Ipke Wachsmuth
IBM Deutschland GmbH
Dept. 3504 - LILOG

ABSTRACT

This paper presents a proposal how domain-specific knowledge of both conceptual and assertional nature can be structured. The aim is to devise a way that allows large amounts of domain-dependent knowledge to be used by a knowledge-based system while keeping the system manageable. The proposal grounds on findings from empirical research on the acquisition of domain-specific knowledge. It is presented abstractly in the form of principles that are to be understood as a specification rather than a symbol-level description for a representation scheme. The model comprised by these principles suggests domain-specific knowledge to be organized in nested packets of knowledge elements. The central notions of VISIBLE and REACHABLE knowledge are used to characterize static and dynamic access conditions.

I. TWO KINDS OF DOMAIN-SPECIFIC KNOWLEDGE

Over the past years, discussions in the area of knowledge representation have dealt with different representation schemes or languages such as semantic nets, frames, procedural and logical representations /11/. There were arguments as to whether these are competitive or more or less equivalent formalisms. For example, it was argued that network formalisms are but a convenient notation for logical knowledge bases and there was even the call for descriptional adequacy, i.e., to use network schemes that are capable of representing any fact expressible in logic /15/. Other authors /2/ have contrasted network schemes from logical ones as concerning a different set of representational issues. Lately, there has been increasing tendency to consider hybrid representation schemes that account for different responsibilities of the knowledge represented such as in KRYPTON /3/ and FORK /1/. A formal approach of how different types of representation languages can be integrated in hybrid systems has recently been presented by Levesque and Brachman /9/.

The trend toward hybrid systems seems to reflect that there exist different qualities of domain-specific knowledge that complement each other and have their own representational and computational principles. The first one could be characterized by object-centered or conceptual knowledge, that is, knowledge about what things are known in a model of a world domain. This kind of knowledge represents meaning (conceptual content) of known things by forming domain-specific descriptive terms and interrelating them, say, in a semantic net. The second quality concerns what is believed to be true in a world domain or what changes of world states are brought about by certain actions. Such knowledge would, for example, be described in assertions which establish connections between concepts representing entities or sets of entities of the modeled world, or in some sort of means-ends relations like production rules. The fact that makes them different in quality and suggests to treat them separately grounds on the realization that they serve different purposes and that different sorts of inferences are associated with them. The typical inferences carried out in object-centered representations are aimed at objects or sets of objects, such as inheritance of properties, set membership and set inclusion, and type subsumption. In contrast, the other sort of inferences aims at manipulations concerned with establishing (or refuting) facts or invoking processes that yield state transitions in the modeled world.

II. STRUCTURED KNOWLEDGE

An important feature of network schemes is the availability of organizational principles which impose structure on a knowledge base. Associations like ISA and other types expressed between objects define access paths that can be used to manage retrieval in a network knowledge base. While there are natural ways of structuring object-centered knowledge, this is <u>not</u> the case with the part of a knowledge base which represents assertional knowledge. For example, Mylopoulos and Levesque /11/ view as an important drawback of logical schemes the lack of organizational principles for the facts that constitute a knowledge base. They fear that without such principles a knowledge base can be unmanageable. Similarly, a lack of structure for the amassment of rules constituting a procedural knowledge base makes it necessary that all production rules are always matched against the global data base.

What needs emphasis here is the fact that major and important portions of a knowledge base may be of assertional quality, notably for expert systems. The truths, wisdoms, and current beliefs that constitute the scientific body of knowledge in a certain domain of expertise are commonly expressed as propositional statements such as following:

> Consumption of coprinus atramentarius in conjunction with liquor causes a variety of toxic reactions such as headache, nausea, and drowsiness (Coprinus syndrome /4/).

Such statements tie together concepts from quite diverse realms such as botany (fungi), nutrition (liquor with meals), and distorted body functioning. What makes such a statement a domain-specific piece of medical knowledge is the fact that the relation expressed between these diverse concepts may become important when a patient exhibits symptoms that require a doctor's decision as to what treatment seems appropriate.

A semantic network serves well to establish the conceptual content of a signified entity like the inky cap fungus (coprinus atramentarius) by embedding this concept in a botanical taxonomy and by describing its make-up from components. In contrast, a piece of assertional knowledge uses the concept signifiers ("coprinus atramentarius", "liquor", "nausea", etc.) to establish a connection between these diverse concepts. While it should be possible that properties of a concept can be used when necessary, reasoning does not always need a recollection of conceptual content. For instance, the identification of possible causes of symptoms in order to judge about treatment may involve a large body of assertional knowledge to be searched.

Computationally, it does not seem easy at all to apply large amounts of domain-dependent knowledge /8/. Thus, with very large and complex knowledge bases on the horizon, a way of structuring domain-specific knowledge that incorporates assertional or means-ends types of knowledge seems desirable in order to obtain knowledge bases that are manageable.

Psychologically oriented research under the novice-expert paradigm has suggested that a crucial feature of man's proficiency in making use of domain-dependent knowledge comes about from the way it is structured. This structure may deviate from criteria of scientific rationality and rather group knowledge around certain domains of experience and typical application cases /5/. The approach presented in the present paper is based on an empirical investigation of such a thesis with the intent to identify organizational principles in human knowledge which include the structuring of both conceptual and assertional knowledge.

III. EMPIRICAL RESEARCH

A large body of qualitative (interview) data from an extended clinical teaching experiment on the acquisition of mathematics knowledge reported on elsewhere /14/ was analyzed to make observations about the genesis of domain-specific knowledge structures and of their static and dynamic features. Along a one-year teaching and observation period, the gradual development of selected students' ability to answer questions and deal with problems involving fractions was recorded. No propositional "products" such as rules were taught to the students. Instead, there was ample occasion for them to make observations and gain experience how concepts in the chosen domain are interrelated.

It was found that (1) students' competence grew initially through their dealing with task situations in an interpretative fashion, i.e., students exploited features of the conceptual entities in the field to answer questions and find problem solutions; (2) students showed strong tendency to abstract observations interrelating concepts in conditional statements (rules) that they accumulated to the repertory of things they know about, and to perform with, the conceptual entities in the field. Such rules were considered as representing belief particles making up the competence of individual subjects, as a potential for generating action /12/. For selected topics, the repertory of rules subjects possessed up to the end of the teaching experiment was identified from the interview data. As was evident from subjects' verbal explanations, they would recognize applicability of a rule by matching rule conditions with task information.

With respect to the question addressed in this paper, the following issues were of interest: How is such a repertory of domain-specific knowledge utilized in applied situations? Are all rules always attempted? Is full use of all resources always made? If there are any restrictions, what are their features and characteristics? Can these serve to extract general principles comprising a model of a structured representation of domain-specific knowledge?

Of course, there is no way to observe structure in human knowledge other than through inferring it from subjects' behavior. To this end, several complex problem solving tasks were presented toward the end of the teaching experiment which required a coordinated use of rules from among the repertory the subjects had acquired (see /15/ for detail). Evaluation of behavioral data from task-based interviews gave strong indication that performance differences across subjects depended not only on the soundness of their rules but also on the way these appeared to be accessible. The crucial observation is that such pieces of domain-specific knowledge are not assembled as an unstructured collection but that they appear to be grouped in a way allowing subjects to separate out subbodies of domain-specific knowledge they think relevant for use in a task situation. By way of extrapolation, this observation could serve to explain the general problem-solving ability of human beings, namely, by their ability to access appropriate subbodies of knowledge based on clues from a task situation.

Instead of giving details, attempt was made here to elaborate general principles characterizing those observations that seem relevant for structuring domain-specific knowledge. Each of the nine principles presented in the following section is motivated by certain empirical observations. Altogether, these principles are understood as a specification for a representation scheme for a structured knowledge base.

IV. PRINCIPLES FOR STRUCTURING

Adopting Newell's slogan equation, REPRESENTATION = KNOWLEDGE + ACCESS /12/ we will have to concern ourselves with (1) the organization of a body of knowledge "in a form that can be used to make selections of actions in the service of goals" and (2) the way how particular knowledge in a structured body of knowledge is accessed such that it "can be used by the larger system that represents the knowledge about goals, actions etc." (all quotes see /12/, p.114). It is not important what kind of pieces of domain-specific knowledge compound the body of knowledge to be structured. We just assume that each one constitutes an identifiable statement interrelating domain-specific concepts that asserts something held for true in a modeled world. Thus, we consider a collection of logical sentences or production rules or any means-ends relations as givens which hereafter will be referred to by the term, knowledge elements.

The first three principles pertain to the way how the knowledge elements are organized in a knowledge base (KB). This arrangement is viewed as permanent until a possible augmentation of the KB takes place. The other principles concern the way in which structured knowledge is accessed and made available to the knowledge-based system (KBS).

Overall, the principles specify a representational scheme for a KBS abstractly, without any commitment to particular programs. Additional structuring features of a syntactic nature might be brought in by a particular implementation, e.g., when representing a KB as a connection graph of first-order logical sentences /7/ or when using a restriction strategy like set-of-support for efficient theorem proving /18/. As pointed out by Levesque and Brachman /9/ in elaborating on Newell's /12/ recommendations, such decisions concern an entirely separate issue that has widely been investigated in automated theorem proving.

1. Principles characterizing the organization of knowledge

1.1 Principle of packing knowledge elements

> Collections of knowledge elements that pertain to a specific domain of knowledge are comprised in a packet. We say the packet owns these knowledge elements. A packet may properly contain further packets of knowledge elements that constitute identifiable subbodies of more specific knowledge within the outer packet.

This principle is visualized in Figure 1. Within the most general packet P1, the packet P3 (or likewise P2) comprises more specific knowledge contained in P1 (thus, owned by both P3 and P1), with P4 being still more specific than P3. The decision what knowledge is considered more specific than other knowledge is a separate issue that may involve heuristics. A criterion for a knowledge element k to be "more specific" than those in a collection of knowledge elements k1,...,kn could be that a reasonable body of problems can be dealt with without using k. "More specific" knowledge might also concern ways how the more general knowledge around it is used in certain contexts.

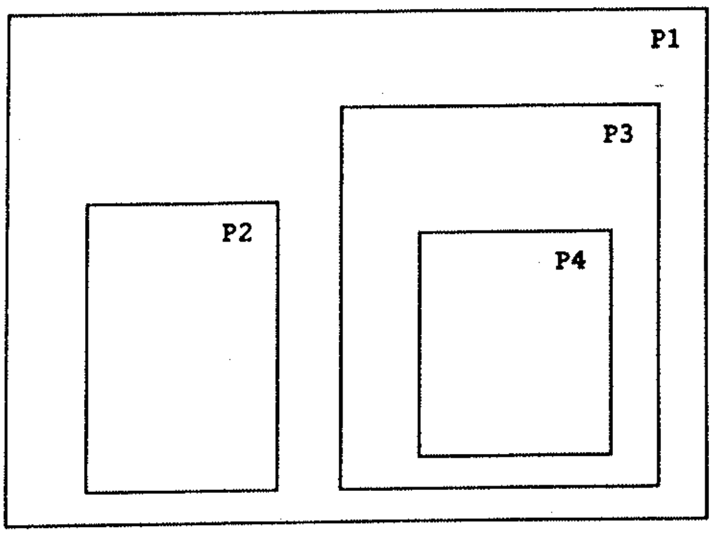

Figure 1

1.2 Principle of competitive knowledge

Collections of knowledge elements that concern alternative methods or views in a given domain of knowledge are packed separately within the surrounding packet. Such packets is referred to as competitive.

In Figure 1, P2 and P3 (but not so P3 and P4) depict competitive knowledge packets. The intent of this principle is to make only one alternative, at a given time, available for use by the KBS as will be provided for by further principles (2.1, 2.2).

1.3 Principle of local consistency

The collection of knowledge elements in one packet must not permit conclusions that are contradictory (or actions that are incompatible). Only then may a packet P contain contradictory (or incompatible) knowledge elements if they are packed separately within P. A collection of knowledge elements satisfying this principle is called locally consistent.

This principle reflects the fact that a method devised to guarantee global consistency can prove computationally intractable. The intent is to restrict consistency checks to packed subcollections of knowledge elements to be performed at any incremental augmentation of a KB. It would also allow "alternative worlds" to be modelled within a KB. According to this principle, P2 and P3 in Figure 1 may contain inconsistent knowledge elements, but not so P3 and P4.

These three principles describe how a collection of knowledge elements can be structured by way of set containment. Of course, such a structure cannot be directly observed from the empirical findings. However, the structural principles are compatible with what was gleaned from the behavioral data. We now proceed to describe how knowledge in a KB satisfying the above structuring principles is accessed. There will be static and dynamic access conditions.

2. Principles characterizing static access conditions

2.1 Principle of eligibility of knowledge elements

The knowledge elements owned by a packet P are conjointly eligible for use by the KBS when their packet P, or a packet within P, is tagged ACCESSED, but only as far as they are not also owned by a packet contained within the one tagged ACCESSED. We say a knowledge element (or a set of knowledge elements) eligible for use is VISIBLE. All knowledge elements packed separately from the packet tagged ACCESSED are not eligible.

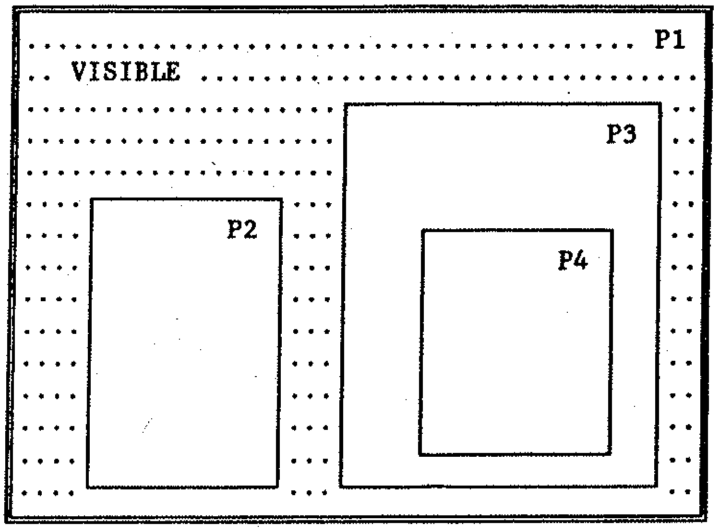

Figure 2a

In Figure 2a, the double welding of P1 is used to depict that P1 is currently tagged ACCESSED. That is, the collection of knowledge elements that are in P1, but not in P2 or P3, are VISIBLE. In Figure 2b, P3 is tagged ACCESSED, that is, the knowledge elements in P3 and in the surrounding packet P1 are VISIBLE. The knowledge elements in P2 and P4 are not eligible for use by the KBS in the access condition shown.

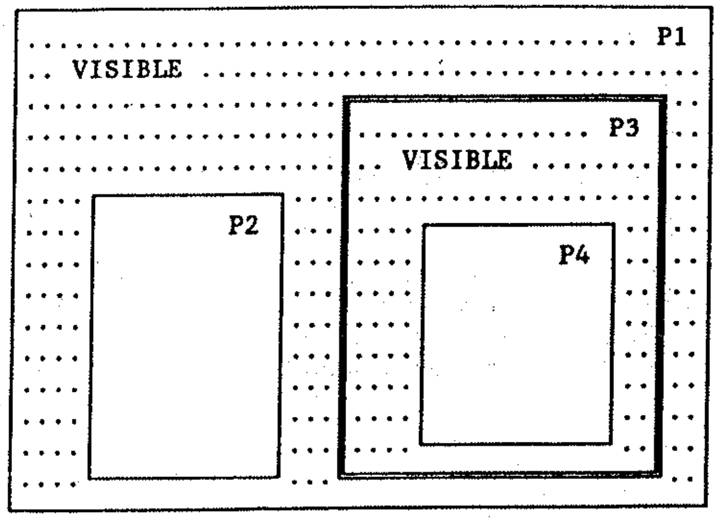

Figure 2b

2.2 Principle of single access to packed knowledge

Only one packet at any given time may be tagged ACCESSED.

This seems restrictive but is only posited here to keep things straight for the basic model. The meaning of "multi-access" needs separate discussion postponed at the present time. Multiple access would allow to reason with competitive knowledge at one time which would make it possible to obtain (or, detect!) contradictory statements among VISIBLE knowledge.

2.3 Principle of reachability of knowledge

When a knowledge packet P tagged ACCESSED owns knowledge elements that are also owned by a packet Q within P, then the set of knowledge elements in Q (or likewise, the packet Q) is REACHABLE. A collection of knowledge elements packed separately from the one tagged ACCESSED is NOT REACHABLE.

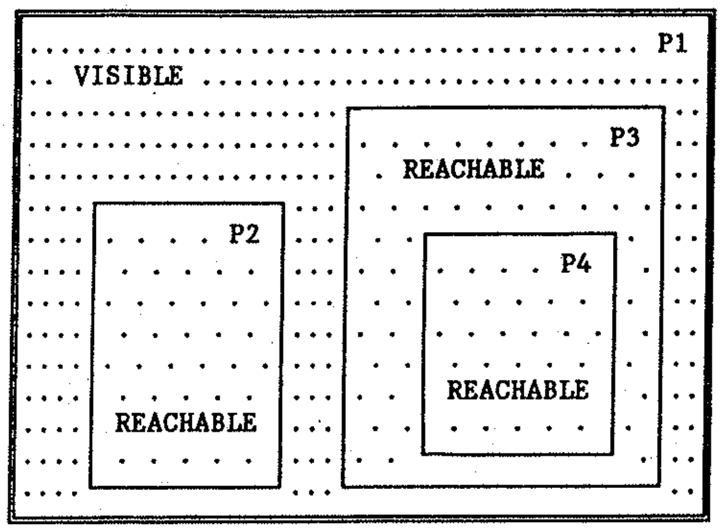

Figure 3a

In Figure 3a, P1 is tagged ACCESSSED and thus P2, P3, and P4 are REACHABLE. In Figure 3b, P3 is tagged ACCESSED, hence only P4 is REACHABLE while P2 is not (and neither VISIBLE). This principle attributes a special role to knowledge elements packed within the packet tagged ACCESSED which is reflected in a dynamic access condition (3.1).

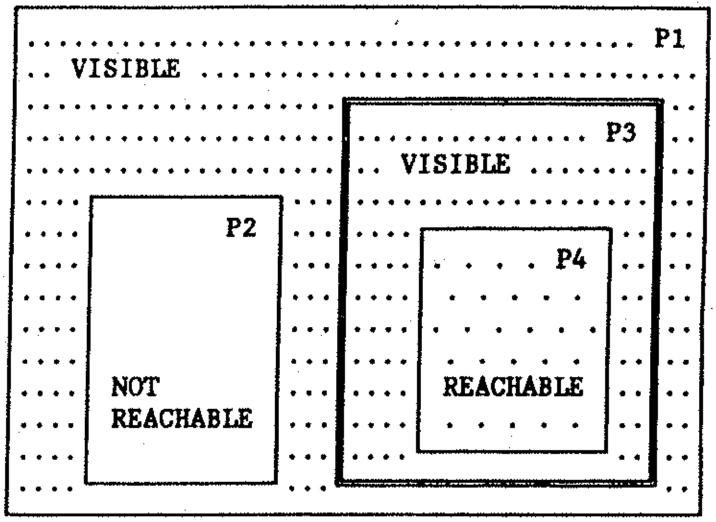

Figure 3b

Overall, static access conditions are characterized by these three principles in splitting the notion of accessed knowledge into VISIBLE and REACHABLE knowledge.

3. Principles characterizing dynamic access conditions

Dynamic access conditions concern the way how the ACCESSED tag is moved around in the structured KB by some control strategy. There may be global control having to do with domain-independent problem-solving strategies, agenda setting, goal selection, etc. These may bring about a KBS's ultimate decisions to act (which may include the need to use certain knowledge from the KB) whereas a KB, by itself, can only support potential ways of acting (possibly competitive ones). However, the way how a KB is structured and what sorts of knowledge elements are packed together does embody some sort of local control in that it constrains the succession in which access to knowledge is attempted.

In general, the empirical observations called upon here say much about human cognitive functioning in terms of how one is able to act on the basis of an enormous repertory of knowledge elements without getting confused by having to face all of them most of the time. The findings suggest that a critical feature of human intelligence lies in a dynamic partitioning of the total knowledge in "visible" and "invisible" parts such that the visible part is normally small enough to be computationally tractable. To prepare grounds for a possible exploitation of this feature in a KBS, attempt is made here to capture some observations in principles of dynamic access conditions.

3.1 Principle of structure-dependent access to knowledge

> When dealing with a task situation on the basis of knowledge currently VISIBLE turns out unsuccessful, the ACCESSED tag is moved to one of those knowledge packets REACHABLE next.

This principle reflects the empirical observation that "zooming in" or "focussing" within a packet of domain-specific knowledge is given preference over "wandering." It suggests that, given that a certain domain was found relevant, more specific knowledge in that domain is accessed next (as far as there is such). Thereby, while the VISIBLE part of a KB gets larger, the REACHABLE part gets progressively smaller (see Figure 3a,b). (The question what is to happen when the resources of a packet are exhausted and competitive knowledge is available is left open for treatment in a particular implementation. If desired, backtracking would allow a KB to be traversed totally. In this case, the advantage of a well-structured KB over an unstructured one might lie in a higher chance to find the "right" piece of knowledge soon.)

3.2 Principle of keyword-dependent access to knowledge

> A means to tag a packet of domain-specific knowledge ACCESSED is the finding of certain concept words (or any sort of symbol) directly associated with knowledge elements in this packet. We refer to such a word as keyword.

This principle suggests to include vocabulary terms (concepts signifiers) among knowledge elements associated with those concepts within a packet. It reflects the empirical observation that rapid access to certain knowledge is often triggered by wordings or technical terms in conveying a question or problem statement. It might even be the case that this interaction, or association, between term words and knowledge elements constitutes a primary means of access that may also be involved in choice making among competitive knowledge packets.

3.3 Principle of persistence of access conditions

> Upon completion of a goal, the current ACCESSED tag persists as a start-off condition for the partitioning state of the KB when the next goal is issued.

Again, this principle is suggested by empirical observations. As further task-descriptive data (or queries, or sentences in a discourse) are issued to an individual, the recent history (previous discourse) may influence the way how these data are processed, at least when there is no break in coherency. This feature might be referred to as "mind set."

V. RELATED WORK

LAKOS1 and LAKOS2 are protoype versions of KBS that use a representation scheme exploiting the above principles of structuring domain-specific knowledge (both implemented in Prolog). Structured assertional knowledge bases for LAKOS1 were specified to model student behavior with respect to answering questions about fraction problems. The packet construct was used to model aspects of contextual boundness of individual students' mathematics performance, including the reproduction of inconsistent behavior as it was observed across different situations /17/. Conceptual knowledge was incorporated only so far as concept words together with symbols denotating their referents were included in knowledge packets containing competency rules dealing with concept referents. That is, the conceptual content was defined totally through the set of beliefs and ways to act accessible in the context of concept words.

LAKOS2 has a structured assertional KB concerned with poisonings by mushrooms. Here, concept-word/referent pairs are likewise included within packets as a link to conceptual (object-centered) knowledge expressed in an inheritance hierarchy (botanic taxonomy) for fungi. The object-centered component can be viewed as an "orthogonal" substructure within the structured domain-specific KB. So far, the system is experimental in that only portions of the taxonomy and a selection of assertions were implemented to set up the overall structure of the KBS.

The feasibility of the structural approach for a large KB that represents domain-specific world knowledge in a natural language understanding system is currently being explored /10/. The application domain chosen is "region" and the body of texts to be understood by the system is concerned with hiking tours in the Alsace. It is planned to use the packet construct as repository for different aspects such as geographic facts, subregions, localities, hiking routes, objects of interest, etc.

VI. CONCLUSIONS

The proposal presented in this paper characterizes domain-specific knowledge as an organized repertory of knowledge elements. The notion of structure is based on cognitive principles and is independent of particular representation languages for knowledge elements. To the author's knowledge, no such approach has yet been proposed[1]. The static and dynamic access conditions give rise to a view of a finite set of KB partitions each of which characterizes a set of possible worlds. While the completeness and inconsistency of a structured KB cannot be guaranteed, the notion of local consistency restricts consistency checks to the domain of VISIBLE knowledge and might prove computationally tractable most of the time. Since knowledge pertaining to certain domain is packed, global inconsistencies seem less likely. However, a mechanism should be provided for which gives notice of the discovery of inconsistencies at run time so that corrective action can be taken.

The principles are not claimed to be comprehensive; there might be additional ones yet to be formulated. In turn, only some of the principles might be realized in an actual implementation, depending on the particular problem domain or purpose of a KBS. It should also be understood that the principles are intended for improving manageability of large knowledge bases containing diverse knowledge. A conclusion near at hand is that knowledge packets might be encapsulated as modules where "module" is understood as a "responsibility assignment" /13/.

Several issues need still to be dealt with such as a notion of multi-access and more general structuring principles that allow knowledge packets to overlap. These are the subject of work in progress.

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1 Hendrix /6/ has proposed a method of organizing network knowledge bases by grouping objects and elements of relations into partitions organized hierarchically that at first sight has some similarities to the approach presented here. Other than in that proposal, no attempt is made here to expand logical sentences in networks. Rather, the knowledge elements in a packet are considered as "sentential chunks" with the only intent to design a method for electing or ignoring certain knowledge elements for use by the KBS.

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