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A Two-Tiered Approach for Organizing Slots in Large, Frame-Structured Knowledge Bases

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Slots represent semantic relations and play a major role in frame-based representation systems; they not only act as an "instruction set" for knowledge entry but also support most forms of inferencing. Thus, the organization of slots merits a systematic study in its own right. A taxonomic approach formalizes the organization of the slots and provides a principled interpretation for their semantics. We discuss the organization of slots from three different perspectives—relation-element, slot-use, and slot-argument—and propose that all three are useful in providing interpretations for slots.

We argue that each individual view, by itself, does not offer sufficient semantics for slot organization. On the other hand, forcing all perspectives together destroys the clarity of a principled taxonomy. Therefore, we propose using two taxonomic views: A first taxonomy for slots is based on the relation-element and slot-use views; this taxonomy is domain-independent and promotes knowledge reuse. A second taxonomy, based on a slot-argument view, is domain- dependent and parallels the nonslot taxonomy.

1. INTRODUCTION

As knowledge-based systems become larger, knowledge management becomes more complicated. The ensuing problems include knowledge understanding, retrieval, consistency, and modification. A principled organization of a knowledge base is critical for manipulating knowledge effectively. In a frame-based system, slots store all the information needed for processing knowledge. Therefore, a principled slot organization is important for effective knowledge-base management.

The goal of this proposed research is to explore and develop knowledge representation methodologies that support the organization of slots in large frame-structured knowledge bases. In this section, we outline our motivation for organizing slots and identify the associated research problems. Then we introduce the background for the proposed research and other related work. In Section 2, we discuss three different perspectives that define the uses and meanings of slots in a frame-based knowledge representation system, and we argue that these views can supplement one another for a deeper understanding of slots.

In Section 3, we present a two-tiered approach that expresses each perspective separately, yet unifies the views synergistically. The relation-element view is used to define individual slots (as simple classes) and the slot-use view is used to define groups of slots (as metaclasses); the resultant taxonomy of slots is domain-independent. The slot-argument view, which also uses classes and metaclasses, parallels the nonslot ontology, is domain-dependent, and provides a second slot taxonomy. In the final section, we draw conclusions and present the status of our research.

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1.1. Motivation

Although much research has been done on the classification of concepts, there has been little research on the classification of semantic relations among concepts from a knowledge-representation perspective. There are many reasons why the organization of slots deserves a systematic study. Slots play many critical roles in frame-based representation systems, such as:

- identifying concepts in the knowledge base. The completeness of the semantics for concepts depends on the richness the slots used as description elements.
- describing facts related to the concept. A frame-based system uses slots to infer implicit knowledge from the asserted facts.
- implementing special inference mechanisms for the specific purposes, such as problem-solving methods.

Because the abstract features of slot concepts are not as describable as nonslot objects, more effort is required to characterize and represent their meaning. However, this effort is worthwhile since the organization of slots affects the system's inferencing structure, which, in turn, determines the conclusions the system can make.

Besides acquiring and representing knowledge, a critical issue in large-scale knowledge system design is to develop techniques for maintaining, reusing, sharing, and extending existing knowledge bases [Neches et al., 1991]. The need for slot reuse can be addressed from the following perspectives:

Modification: To use existing knowledge, we often need to modify it to match our current requirements. The easier it is to modify existing knowledge, including any underlying assumptions [Skuce and Monarch, 1990], the better are our chances of reusing the knowledge.

Sharing: The easier it is for disparate users to understand the knowledge represented, the greater are the chances of sharing the knowledge. To share knowledge among different users, we also require a common language and standard format.

Portability: Domain-independent general knowledge is more likely to be ported and reused than domain-specific knowledge.

Specialization: If a domain-specific concept being represented can be expressed by specializing an existing general concept in an ontology, then the ontology is reusable. Thus, the structure and semantics of the upper model of the ontology are important in ensuring reusability.

Consider an example of knowledge reuse involving slots. Suppose we wish to encode a relation *r1* between class *A* and class *B*. We find an existing slot, *slot1*, that seems to carry the correct

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semantics, but maps from class *A* to class *C*. There are at least four choices, each with advantages and disadvantages:

Choice: Create a new slot that maps from class *A* and class *B*.

Advantage: We have a slot with the semantics we require.

Disadvantage: Another slot is added to the knowledge base. This adds to the overhead in searching for candidate slots.

Choice: Modify the existing slot to make it more general. That is, change the range of the existing slot from *B* to the most specific subsumer of *B* and *C*.

Advantage: There is no addition to set of slots. Existing uses of the slots are not affected.

Disadvantage: The semantics of the existing slot is "diluted." In the extreme case, if a slot maps from the top-level concept *(Thing)* to *Thing*, it means almost nothing. There would be no class restrictions at all in using the slot.

Choice: Change the ontology by making the *B* a subclass of *C*.

Advantage: Again, there is no addition to set of slots, and existing uses of the slots are not affected.

Disadvantage: There may be no principled basis for making the subclass link, and making such a link simply to accommodate the use of a slot is not sufficient justification.

Choice: Add the potential slot values (instances of class *B*) as direct instances of the existing class *C*; scrap class *B*.

Advantage: Again, there is no addition to set of slots, and existing uses of the slots are not affected.

Disadvantage: There may be some other need for class *B*, which we now lose.

The selection of one of these choices depends largely on the current state of the knowledge base.

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1.2 Background

Minsky [1981] proposed a form of knowledge representation called the frame, which he defined as "a data-structure for representing a stereotyped situation." Each concept that we wish to represent may be expressed as a frame, which is a structure made up of slots that contain each constituent element of the concept. Slots, which associate one frame to others, play a major role in the implementation and performance of frame-based representation systems. In this section, we first describe slots in a large frame-structured system and a set-theoretic semantics for slot knowledge. Then we outline a taxonomic approach to organize slots in the frame-based system.

1.2.1 Slots in a Frame-Structured System

In a frame-structured knowledge base, frames are represented by a collection of slot-value pairs. Each slot name may be associated with a corresponding relation and a corresponding predicate. The notation *object-attribute-value* is used to indicate that on the frame *object* there is a slot *attribute* having an entry of *value*. This notation is equivalent to the predicate calculus assertion *attribute(object, value)* and to the set notation for relations *<object, value>* $\in$ *attribute*.

As a knowledge base grows in size, practical problems arise. When a user represents a new frame — either slot or nonslot — in the knowledge base, he must use a subset of the existing collection of slots. If suitable slots are not available, the user must create them. In a sense, the set of currently available slots acts as an "instruction set" for knowledge entry. As more and more knowledge is added to a large knowledge base, the number of slots increases and so does the probability that needed slots are already represented; however, *finding* the slots becomes more difficult unless a principled scheme for organizing and retrieving them is devised.

Cyc [Lenat and Guha, 1990], under development for the past eight years at the Microelectronics and Computer Technology Corporation, Austin, Texas, is attempting to encode into a computer common-sense knowledge about the real world, along with mechanisms for reasoning about that knowledge. Cyc's knowledge base currently contains more than 1,000,000 assertions organized as 35,000 frames of which 5,000 are relations (slots).

These slots are loosely organized according to several different schemes. For example, they are organized into two major categories: *bookkeeping* and *defining*. Bookkeeping slots (such as *myCreator, myCreationTime,* and *copiedFrom*) store system information that may assist users in entering and maintaining knowledge. Bookkeeping slots carry no semantics and are not used in classification. The defining slots are subdivided into classes for extensional, intensional, and taxonomic slots. We proposed to examine these categories as a starting point for determining principles for organizing categories of slots.

1.2.2 A Set-Theoretic Semantics for Slot Knowledge

The semantics of a binary slot in Cyc is that of the *binary relation*. A binary relation R is defined as a set of ordered pairs formed by specifying a subset of the Cartesian product of two sets A and B, called the domain and range, respectively [Stanat and McAllister, 1977]. In addition to the domain and range, a relation is characterized by a mapping that specifies which ordered pairs belong to the relation. The mapping may be either *intensional* (specified by a rule) or *extensional*

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(specified by listing the ordered pairs). An ordered pair in the relation $R \subseteq A \times B$ is denoted $<a, b> \in R$, where $a \in A$ and $b \in B$. Corresponding to each binary relation R is its *inverse* R^{-1}, such that if the ordered pair <a, b> is an element of R, then <b, a> is an element of R^{-1}. As noted previously, the frame notation $a \cdot R \cdot b$, set notation $<a, b> \in R$, and predicate calculus notation $R(a, b)$ are equivalent.

It is possible for one slot to be a specialization of another. For example, the slot *hasDaughter* is more restrictive than *hasChild*. In Cyc, this notion is implemented by the use of a special taxonomizing slot for slot frames, which this paper refers to as *slotSpecializationOf* for parallelism with *subsetOf*. This parallelism is desirable because the notion of slot specialization carries the semantics of set inclusion — the extensional representation of a slot is a *set* of ordered pairs. Thus, given that a slot S_1 is a slot specialization of S_2 ($S_1 \subseteq S_2$), if $<a, b> \in S_1$, then $<a, b> \in S_2$. This constraint is enforced in the Cyc representation language.

Representing slots as full-fledged frames on equal footing with object frames as in Cyc offers a major advantage: the properties of the slots can be expressed declaratively. This representation can be used to enhance the inferencing power of the knowledge base [Huhns and Stephens, 1989]. In addition, this representation can be used to enforce constraints for slots: a slot may appear only on a frame that is an instance of the slot's domain; the slot's value must be an instance of the range; and the number of slot entries must agree with the entry format requirements [Lenat and Guha, 1990].

Frames are used in Cyc to represent both classes, which have instances, and individuals, which do not. For this reason, it is important to distinguish between *own slots* and *member slots* [Fikes and Kehler, 1985]:

> **Own slots** describe a frame as an instance of a class, *i.e.*, own slots describe the frame's own properties. For example, the class *GraduateStudent* might have aggregate properties, such as *averageAge* — an own slot for the class frame that is not appropriate for a particular graduate student.
>
> **Member slots** describe a frame as a class, *i.e.*, member slots describe the properties of the frame's instances (members). For example, the class frame *GraduateStudent* might have the member slot *age*, which would appear on every instance of the class.

In Cyc, any frame can have own slots, but only class frames can have member slots.

1.2.3 Taxonomic Approach for Organizing Slots

One of the prime concerns of knowledge representation is how to organize knowledge for efficient retrieval and effective reasoning. A taxonomic approach provides a formal structure for organizing the concepts (both slot and nonslot) in a knowledge base. A taxonomy defines and describes classes of concepts, and provides a generalization-specialization relation between classes. Such a taxonomy supports reasoning activities such as classification and inheritance.

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We view slots as simple classes (a set of *n*-tuples) that are instances of slot categories, which are expressed as metaclasses. A separate interpretation of the generalization-specialization relation is used between pairs of slots (*slotSpecializationOf*) and between pairs of slot categories (*subclassOf*). At the top level, such a taxonomy is composed of primitive slots and slot categories; all other slots and slot categories are specialized from these primitives.

We expect the outcome slot taxonomy should

- provide explicit description about the underlying view for the taxonomic model,
- support representational convenience and retrieval efficiency,
- represent relationships among slots at different levels of abstraction,
- prevent the duplication of slots that have the same meaning,
- maintain a single category to describe slots that have common inferential features,
- offer the user a hierarchical view of the inferencing capability of the system,
- express different perspectives for slot organization separately, yet unifies the views synergistically, and
- promote slots reuse by setting a domain-independent slot taxonomy.

In summary, we can organize slot concepts into a taxonomic hierarchy that stores information at appropriate levels of generality and make it available to more general slot concepts. For example, the slot *componentOf* has a more specialized abstraction than the slot *partOf*. Therefore, we may infer all the *components* of a personal computer (such as keyboard and disk drives) are also *parts* of the personal computer. This illustrates the slot specialization relationship between individual slots.

On the other hand, we can group certain slots into classes based on the slots' common inferential features; these features can, in turn, be transferred to more specific slot classes by means of *inheritance* [Touretzky, 1986]. For example, a class containing slots that are used to constrain the *value* of slot entries is more specialized than a class containing slots that offer more general restriction functions, such as restricting the *number* of entries. This hierarchical structuring helps us to recognize the constraining features for the system.

1.3 Related Work

The principle of categorizing knowledge has been studied in many different areas such as cognitive science and information science [Nagao, 1990]. However, compared to ontologies for general concepts, slot organization has received little attention from the AI community until recently. Our work in organizing slots builds on research from two areas: (1) knowledge representation systems that enforce the classification of concepts based on term subsumption and (2) linguistics and

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cognitive psychology research that describes semantic relations in terms of more basic relational elements.

1.3.1 Term Subsumption

To be useful, knowledge must be organized. One method for organizing knowledge in AI systems is to use the notion of subsumption between concepts [Patel-Schneider *et al.*, 1990]. The KL-ONE knowledge representation system [Brachman and Schmolze, 1985] and its many derivatives rely on term subsumption, which imposes a partial order — a taxonomy — on the concepts.

For one term to subsume another, the definitional features of the subsuming term must be more general than definitional features of the term being subsumed [Abrett and Burstein, 1987]. For example, the class *Birds* is more general than (and therefore subsumes) the class *Parrots*, because parrots have additional properties that distinguish them from birds in general.

When entering knowledge into KL-ONE-type systems, a user specifies the definitional properties of an concept, and the classification algorithm computes subsumption. A user may be required to supply an (indirect) taxonomic link to primitive concepts [Brachman and Schmolze, 1985] — called primary conceptual descriptions by Woods [1991]. Primitive concepts are undefined terms used to denote incompletely described or undefinable concepts: those concepts for which necessary and sufficient conditions cannot be stated [Doyle and Patil, 1991]. Primitive concepts about which we can say nothing are referred to as *atomic* [Woods and Schmolze, 1992].

In this discussion, we must distinguish between assertions entered by a user — told information— and assertions computed by a classifier — derived information. For example, suppose that *Person* is a primitive concept and that *Woman* is a specialization of *Person* because of *Woman's* additional property *gender·Female*. To enter the concept *WomanGolfer* — a person of female gender who plays golf — a user might initially link *WomanGolfer* to *Person* and specify the properties *gender·Female* and *hasHobby·golf*. The classifier then computes the position of *WomanGolfer* as a direct specialization of *Woman* — *WomanGolfer's* most specific subsumer. The taxonomic link from *WomanGolfer* to *Person* now exists via the transitive closure of subsumption.

Keeping a slot taxonomy consistent is critical for ensuring that different users treat slot concepts in the same way; this consistency is necessary if knowledge is to be reused. To maintain consistency of represented knowledge, the KL-ONE approach enforces automatic classification of concepts [Lipkis, 1982], [Schmolze and Lipkis, 1983]. However, this approach suffers from two limitations [Doyle and Patil, 1991]. One restriction trades expressiveness for classification completeness. The other is the inability to classify primitive concepts since a primitive concept has no complete set of distinguishing properties. Moreover, the few slot-forming operators (such as domain and range) supported by the KL-ONE family of languages [Patel-Schneider, 1987] do not, in our opinion, provide adequate semantics to maintain a slot taxonomy.

1.3.2 Relation Element Theory

[Chaffin and Herrmann, 1988] review two fundamental ways in which relation knowledge may be viewed. The *unitary semantic entity* view holds that people use relations as indivisible terms in

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explanations and, therefore, do not analyze or decompose them. [Iris *et al.*, 1988] advance a unitary view for the part-whole relation by describing it as comprising four distinct relations involving functionality, the segmented whole, collections, and sets. On the other hand, the *relation element* theory proposes that people comprehend associations by identifying sets of primitive properties that make up relations between words. The relation element theory appears to offer several advantages over the unitary view:

- Relations may be represented in the same manner as concepts, that is, as collections of definitional properties. This representation allows relations to be treated as first-class concepts in a knowledge base.

- Relations elements can be used to explain and predict plausible compositions among relations [Huhns and Stephens, 1989].

Based on a survey of psychological and linguistic literature, Chaffin and Herrmann develop a taxonomy of 31 relations, organized into the following five major families: contrasts, similars, class inclusion, case relation, and part-whole [Stasio *et al.*, 1985]. They identify a set of relation elements that can be used to describe, distinguish, and classify the relations. Each relation element is a fundamental property that holds between an element of the domain and an element of the range of a (binary) relation. These elements provide a basis for explaining the organization of relations into families, as well as similarities among relations within a single family and similarities among the different families. In experiments in which subjects were asked to classify examples of the relations and to make judgements about the similarities of relations, the theory of relation elements accounted better for the similarities between and within families of relations than did a unitary semantic view.

In their research on taxonomizing meronymic (part-whole) relations, [Winston *et al.*, 1987] identify six types of meronymic relations, each distinguished by three binary-valued relation elements: *functional, homeomerous*, and *separable*. [Cohen and Loiselle, 1988] identify two deep structures for relations, *hierarchical* and *temporal*, each having a *direction*. Although not explicitly stated, the directions are from hierarchically superior to inferior, from temporally past to future, and from subclass to class. In their study, each relation has one of the following structures: hierarchical only, temporal only, or both. However, neither [Cohen and Loiselle, 1988] nor [Winston *et al.*, 1987] consider the domain and range of a relation as definitional properties.

[Huhns and Stephens, 1989] extend the research efforts cited above and find ways in which they complement each other. A major contribution is the consideration of relation composition from the mathematical basis of set theory. The use of a formal definition of extended composition of relations leads to the conclusion that typing of the domain and range elements restricts composition, independently of any other relation attributes. Thus, the domain and range of a binary relation should be considered as definitional for the purposes of classifying relations. In addition, Huhns and Stephens explicitly consider the hierarchical nature of the inclusion relations, as suggested by [Cohen and Loiselle, 1988].

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2. A FRAMEWORK FOR SLOT ORGANIZATION

In a frame-based system, slots are used to recognize concepts and to infer implicit knowledge. The more the system knows about the meaning of slots, the better it can perform. Slots can be organized in different ways depending on their intended application. For natural language understanding, slots are used to represent case relations or specific linguistic primitives [Sowa, 1990]. In problem-solving domains, slots are used to focus on generic tasks and inferential structures for problem solving [Steels, 1990]. Researchers concerned about concept classification emphasize slots that represent definitional knowledge [Swartout and Neches, 1986]. Our goal is to provide a slot organization that

- offers representation convenience and retrieval efficiency,
- expresses the inference mechanisms and enhances the reasoning capability, and
- promotes knowledge sharing and reuse.

To provide a deeper understanding of slots, we have studied them from three different perspectives. The analysis for each perspective comes from answering the following questions:

- What is the specific meaning and information that can be delivered from this view?
- How can we express the notions of specialization- generalization in a principled way for different views?
- What is the inferential potential of the slot taxonomy?
- How will the underlying model of each view support reusability of knowledge?

2.1 Relation-Element View

In this view, a slot can be understood by the nature of its associations. For example, the slot *partOf* has relation elements, such as *functional* and *separable*, that are independent of the objects involved [Winston *et al.*, 1987], [Bejar *et al.*, 1990]. The slot *componentOf* can be characterized as more specialized than *partOf* because the functional feature of *componentOf* is more specialized than that of *partOf* [Stephens, 1991].

An inference that can be drawn from this taxonomy is that a general slot contains all the entries of its more specialized slot based on the relation-element view. For example, all the components of a car (such as wheels, engine) are also parts of the car. Previous work on plausible inferences from the composition of two slots relied heavily on the relation elements of slots [Cohen and Loiselle, 1988], [Huhns and Stephens, 1989]. Maintaining a slot taxonomy based on relation elements helps a user access slots in a neutral way without referring to concepts in an application domain. This feature is particularly useful for knowledge sharing and reuse.

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2.2 Slot-Use View

While the relation-element view is based on a real-world interpretation for slots, the slot-use view is concerned with the function the slots play within the knowledge representation system. For example, we might distinguish those slots used for placing a concept in its taxonomy from those slots that describe some facts about the concept. From a slot-use view, the specialization-generalization relationship represents a specialization in function of the slots. For example, slot facets[1] used to constrain the value or the cardinality of a slot (when used on a frame) have a more specific role than slots used to constrain slot concepts in general. In Cyc the slot classes *SlotValueConstraintSlot* and *EntryFormatConstraintSlot* are specializations of *ConstraintSlot* [Lenat and Guha, 1990].

The slot-use view organizes slots for different types of inferencing. For example, identifying (terminological) slots are used in classification-based reasoning [Woods, 1991], while the descriptive (assertional) slots are involved in other inference mechanisms, such as default reasoning and truth maintenance. A taxonomy of slots based on the slot-use view can help us determine the inferential capability of the system. Furthermore, we can access a slot by knowing how it functions in the representational system. In addition, the slot-use view is domain-independent and supports the reuse of knowledge.

2.3 Slot-Argument View

In this view, we organize slots according to the real-world domain concepts that the slots describe. For example, we might define a slot class called *ProcessDescribingSlot* that contains slots that have *Process* as their first argument. Because this view focuses on the meaning of related nonslot concepts, the slot taxonomy parallels portions of the general ontology: the classification of the nonslot concepts determines the slot taxonomy. For example, the Cyc slot class *LanguageDescribingSlot* is specialized from *IntangibleObjectDescribingSlot* because the concept *Language* is a specialization of *IntangibleObject*. Because of this dependency, the reusability for the slot taxonomy depends on the generality of the nonslot ontology. A reusable ontology of concepts, such as the Penman Upper Model [Bateman *et al.*, 1990], would make it easy to transfer the underlying slot taxonomy to other applications.

3. TWO-TIERED SLOT TAXONOMIES

Parsing a sentence requires natural language notions of denotation and connotation of words, as well as the context of the sentence. We expect that multiple perspectives for a slot's meaning can supplement one another for a more complete and precise semantics for organizing slots. We propose a two-tiered approach that expresses each perspective separately, yet unifies the views synergistically.

To allow each slot to carry dual meanings, we represent own and member properties [Fikes and Kehler, 1985] for slots. For each slot concept, we assign (1) properties that each member of this slot concept can have and (2) properties that the slot concept has on its own. We view an individual

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[1] The term facet is used for attributes of slot concepts; facets are "slots for slots."

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n-ary slot as a simple class whose members are *n*-tuples. The slot is also an instance of some slot metaclass, which groups together slots with common features.

Combining (1) slot metaclasses that represent the slot-use view for a group of slots and (2) simple slot classes that represent the relation-element view for an individual slot, we produce a two-tiered, domain-independent slot taxonomy. For example, based on the relation-element view, the slots *hasFunctionalPart* and *hasStructuralPart* are slot specializations of the most general part-whole slot *hasPart*. But in the slot-use view, the slots *hasFunctionalPart* and *hasColor* become instances of the slot metaclass *IdentifyingSlot*, which is specialized from the more general metaclass *SlotForNonslotConcepts*.

This two-tiered approach is also applied to the slot- argument view for a second slot taxonomy, which is domain-dependent and parallels parts of the general ontology. A simple class represents an individual slot concept, while a metaclass has a group of slots, each of which has "special things" that need to be represented [Lenat and Guha, 1990]. For example, the slot *hasDaughter* can be specialized from *hasChild* by restricting the latter's range to *Female*. Both slots are, in turn, instances of a slot metaclass *PersonDescribingSlot*, which is a specialization of *AgentDescribingSlot*.

4. CONCLUSIONS AND RESEARCH STATUS

Our framework for organizing slots integrates two research domains: (1) the representation and reasoning of large amounts of common-sense knowledge in a frame-based system as a resource to study slot applications, (2) recent results from cognitive science and linguistics in the fundamental properties of relationships among concepts as a foundation to study the terminological properties for slots. We are continuing our previous effort [Stephens, 1991], which is based on the relation-element perspective, by providing additional views for the semantics of slots.

There are two sources of semantics for slots. One is a real-world interpretation, which is based on the linguistic foundation of relations. The other is the functional role the slots play in knowledge representation systems. Both meanings are important and supplement each other. Some slots are more significant in one view, while other slots are easier to interpret from another view. For example, the Cyc slot *slotValueSubsumes* is easier to understand from a slot-use view (as an instance of the slot class that expresses constraints) than from either of the other two views, which are linked to real-world interpretations for slots.

Previous work in representing slots has implicitly used the slot organization views presented in this paper. The self-describing features of the slot-use view have been proposed in early knowledge representation languages, such as RLL [Greiner and Lenat, 1980]. In the Penman Upper Model [Bateman *et al.*, 1990], the slot taxonomy is built under the concept *Process* and many slots parallel the nonslot taxonomy — the slot-argument view. For example, the nonslot taxonomy has the concept *Spatial-Temporal*; the slot taxonomy has *Spatial-Temporal-Relations*.

In Cyc, slots are treated as individual objects belonging to the top-level class Predicate. The slot taxonomy below *Predicate* is a mix of slot-use views (*DefiningPredicate, BookkeepingSlot*), slot-

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argument views (*ProcessDescribingSlot, AgentDescribingSlot, IntangibleObjectDescribingSlot*), and relation-element views (*PrimitiveDefiningSlot, PartWholeSlot*) [Lenat and Guha, 1990].

An explicit picture of slot organization is important for understanding both the semantics of slots and the inferential structure of a knowledge-based system. Users need to know the meaning and function of the existing slots when entering new knowledge into the system; the knowledge-based system needs the semantics of slots for inference and maintenance. This paper's framework for organizing slots from both standpoints is based on

- a model for the taxonomy of slots using a principled interpretation.
- an explicit semantics of slots from each of three separate views to improve understandability.
- a domain-independent slot taxonomy based on the relation-element and slot-use views. Domain independence promotes the reuse of knowledge.
- a synergistic use of taxonomic constructs for organizing slots.

Cyc is being used as a testbed to substantiate the proposed research for the following reasons: (1) Cyc has a large knowledge base and a variety of inference mechanisms that make it a rich environment for study; and (2) Cyc allows the same expressive power for slot concepts as for nonslot concepts. Although Cyc is being selected as the vehicle for conducting the research, the principles developed for organizing slots will be independent of the particular knowledge representation system used.

We are implementing a learning-and-applying cycle to refine our methodology for organizing slots. Our research has been motivated by our experience in implementing a real-world application using the Cyc system [Stephens *et al.*, 1992]. From this experience, we are documenting and analyzing the problems of accessing and reusing the slots in the Cyc's knowledge base. For example, we have found that mixing the perspectives for Cyc's slot concepts destroys the clarity of a principled taxonomy and causes understandability problems. In addition, the tremendous effort required to modify slots for reuse lead to the desire for a domain-independent slot taxonomy. These analyses have lead to the slot organization methodology described in this paper.

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