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Working Notes of the KI'94 Workshop:

KRDB'94
Reasoning about Structured Objects: Knowledge Representation Meets Databases

Saarbrücken, September 20-22, 1994

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Director

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This collection of papers forms the permanent record of the KRDB'94 Workshop "Reasoning about Structured Objects: Knowledge Representation Meets Databases", that is held at the University of Saarbrücken, Germany on September 20-22, 1994, as part of the 18th German Annual Conference on Artificial Intelligence. The workshop is set up to be as informal as possible, so this collection cannot hope to capture the discussions associated with the workshop. However, we hope that it will serve to remind participants of their discussion at the work-

for the database schema. Finally, Wolfgang Benn takes a data dictionary as input and puts a taxonomic layer on top of it in order to produce integrate database schemata and to reason on completeness.

Another area of interest is the relationship of knowledge representation and query languages. Ulrich Hustadt argues against the standard closed-world-assumption in database query languages and votes for an epistemic operator that can stepwisely convert a knowledge base into a database. Klaus Schild augments this argument by his investigation

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Description Logics for Schema Level Reasoning in Databases

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Abstract

Several recent papers point out that the research on Description Logics and their associated reasoning techniques can be profitably exploited in several ways in the area of Databases. We argue that one of the most important aspects of Databases where we can take advantage of Description Logics is the one related to schema level reasoning, i.e., reasoning at the intensional level of a database. This is the case in schema design, schema maintenance, schema integration, schema translation, integrity checking, query evaluation in cooperative information systems, etc. Indeed, on the one hand Description Logics can be seen as very powerful data models, and on the other hand, they can serve as unified formalisms that capture object-oriented, semantic and conceptual data models proposed in the literature. Most importantly, they can provide useful reasoning services in all the above mentioned tasks.

Database Views on KR Classification
— Abstract —

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Abstract. The database models for Object Database Systems (ODBMSs) include many modeling concepts that originate in semantic data models, that were formerly used for database design purposes, or in (object-oriented) programming languages. To some extent, research on data models and query languages for such ODB models has already reached a consensus, not on one particular model or language, but on the core of what should be considered furtheron. Other aspects, such as view support for example, are less common. We argue that the KL-ONE style terminological logics can provide a very convenient basis for the integration of a flexible view mechanism into object databases. KL-ONE defined concepts correspond to database views (classes of objects that are derived by a qeury expression). Updates to such views can be propagated to base classes if the view classes are inserted into the global class(ification) hierarchy. Therefore, object databases need the inference services that KL-ONE systems provide (classification, subsumption, ...). We report on the experiences that we gained in the COCOON project, where this approach was pursued over the last few years.

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Formalization of OODB Models

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1 Introduction

Object-oriented data models represent a current endpoint in the evolution of data models [23]. Their formalization has been attempted in a variety of papers, including [5; 6; 19]. This short paper indicates what we consider the common intersection of these (and other) approaches; we list the relevant features and components, and give an idea of how to formalize the notion of an object-oriented database schema.

An object-oriented data model has to capture a variety of requirements [8; 27], which differ considerably from those that traditional data models have to meet. However, many system developers seem not to care about *formal* models as a solid foundation of their system, but simply design a "data definition language" in which the relevant features can be coded. In our opinion, a formal model for object-oriented databases basically has to capture the same intuitions as models for other types of databases, which are the following:

1. It has to provide an adequate linguistic abstraction for certain database applications.
2. It should provide a precise semantics for a data definition language.
3. It has to be composed of both a specification and an operational part.
4. It represents a computational paradigm as a ba-

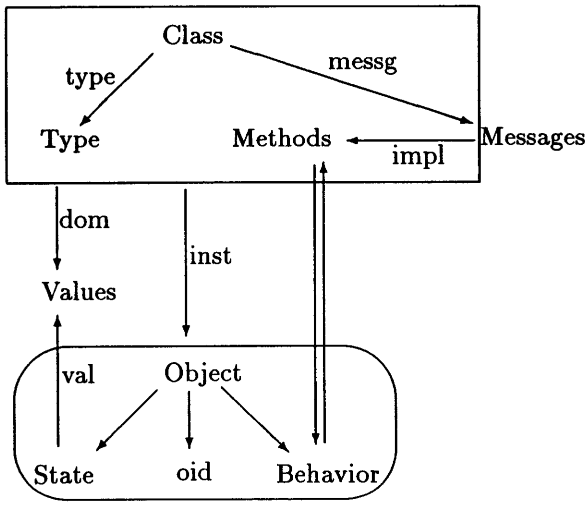

Figure 1: Core Aspects of an Object Model.

S_{behav}); in what follows, we first consider each component in isolation and then indicate how the two interact. We mention, however, that while it is generally agreed that an object-oriented data model has to capture both structure and behavior, the former can be obtained by using the experience from the relational, nested relational and complex-object models class (its external interface), which are internally implemented using *methods* that are executable on objects. Hence, objects have a state *and* a behavior; in addition, they are uniquely identified. Messages are specified by providing a *signature*, and by associating several signatures with the same message name, the latter gets *overloaded*. Not shown in Figure 1 is the possibility to organize classes in an *inheritance hierarchy*; also not shown is the fact that class attributes are allowed to reference other classes, thereby forming an *aggregation lattice*.

We next look at structural as well as behavioral aspects in more detail. Regarding the modeling of structure, more precisely highly-structured information, complex data types are all that is basically needed, since they serve as descriptions for domains of complex values. One way to introduce such types, i.e., to define a *type system* T, is the following:

(i) $\mathtt{integer}, \mathtt{string}, \mathtt{float}, \mathtt{boolean} \subseteq T$;

(ii) if A_i are distinct attributes and $t_i \in T$, $1 \leq i \leq n$, then
$[A_1 : t_1, \ldots, A_n : t_n] \in T$ ("tuple type");

(iii) if $t \in T$, then $\{t\} \in T$ ("set type");

(iv) if $t \in T$, then $< t > \in T$ ("list type").

In other words, a type system is made up of *base types*, from which complex types may be derived using (eventually attributes and) *constructors*. Note that this requires nothing additional but the availability of attribute names. Clearly, other base types as well as additional or alternative constructors could straightforwardly be included. Notice also that here types are not named; for practical reasons, the use of type names may be desirable (e.g., in order to be able to reuse type definitions in various places throughout a schema), and if it is, it can easily be added to the above in the way indicated earlier.

The notion of a domain as a "reservoir" of possible values can be defined as follows; it just has to obey constructor applications:

(a) dom(`integer`) is the set of all integers; dom is analogously defined for `string`, `float`, `boolean`;

(b) $\mathrm{dom}([A_1 : t_1, \ldots, A_n : t_n]) :=$
$\{[A_1 : v_1, \ldots, A_n : v_n] \mid (\forall\, i, 1 \leq i \leq n)\ v_i \in \mathrm{dom}(t_i)\}$;

(c) $\mathrm{dom}(\{t\}) :=$
$\{\{v_1, \ldots, v_n\} \mid (\forall\, i, 1 \leq i \leq n)\ v_i \in \mathrm{dom}(t)\}$;

(d) $\mathrm{dom}(< t >) :=$
$\{< v_1, \ldots, v_n > \mid (\forall\, i, 1 \leq i \leq n)\ v_i \in \mathrm{dom}(t)\}$.

In a structurally *object-oriented* context, the first thing that needs to be introduced beyond complex types and domains as defined above is the possibility to *share* pieces of information between distinct types, or to *aggregate* objects from simpler ones. At the level of type declarations, an easy way to model this is the introduction of another reservoir of names, this time called *class names*, which are additionally allowed as types. In other words, *object types* are complex types as above with the following new condition:

(v) $C \subseteq T$, where C is a finite set of class names.

This states nothing but the fact that class *names* are allowed as types (below we will complement this with the requirement that classes themselves *have* types).

The intuition behind this new condition is that objects from the underlying application all are distinguished by their identity, get collected into classes, and can reference other objects (share subobjects). To provide for this at the level of domains, let us first assume the availability of a finite set OID of *object identifiers* which includes the special identifier `nil` (to capture "empty" references); next, *object domains*, i.e., sets of possible values for objects are complex values as above with the following additional condition:

(e) $\mathrm{dom}(c) = OID$ for each $c \in C$.

Thus, classes are assumed to be instantiated by objects (class-name types take object identifiers as values, in the same way as, say, the `integer` type takes integer numbers as values). Clearly, this alone is not enough, since class instances commonly have distinct sets of object identifiers associated with them. We will show below how that (and, for example, the fact that sometimes inclusion dependencies need to hold between sets of class instances) is captured at the instance level.

The object-oriented paradigm has another dimension for organizing information besides aggregation, which is inheritance, or the possibility to define a class as a specialization of one or more other classes. To this end, a *subtyping relation* is needed through which it can be expressed that a subclass *inherits* the structure of a superclass. Such a relation can be defined in various ways; for example, it can be defined semantically by requiring that the sets of values or instances of types, where one is a subtype of the other, are in a subset relationship. We prefer a simpler, syntactical approach, which has, for example, the advantage that checking subtype relationships can be automated:

Let T be a set of object types. A subtyping relation $\leq\ \subseteq T \times T$ is defined as follows:

(i) $t \leq t$ for each $t \in T$,

(ii) $[A_1 : t_1, \ldots, A_n : t_n] \leq [A'_1 : t'_1, \ldots, A'_m : t'_m]$ if

  (a) $(\forall\, A'_j, 1 \leq j \leq m)(\exists\, A_i, 1 \leq i \leq n)\ A_i = A'_j \wedge t_i \leq t'_j$,

  (b) $n \geq m$,

(iii) $\{t\} \leq \{t'\}$ if $t \leq t'$,

(iv) $< t > \leq < t' >$ if $t \leq t'$.

With these preparations, we arrive at the following definition for objectbase schemas that can describe structure of arbitrary complexity: A *structural schema* is a named quadruple of the form $S_{\mathrm{struc}} = (C, T, \mathrm{type}, \mathrm{isa})$ where

(i) C is a (finite) set of class names,

(ii) T is a (finite) set of types which uses as class names only elements from C,

(iii) type : $C \rightarrow T$ is a total function associating a type with each class name,

(iv) isa $\subseteq C \times C$ is a partial order on C which is consistent w.r.t. subtyping, i.e.,
c isa $c' \Rightarrow \text{type}(c) \leq \text{type}(c')$ for all $c, c' \in C$.

This definition resembles what can be found in a variety of models proposed in the literature, including [17; 19; 20; 25] and others. Notice that it still leaves several aspects open, like single vs. multiple inheritance; if the latter is desired, a condition needs to be added stating how to conflicts should be resolved. Also, implementations typically add a number of additional features, like attributes as functions [22; 29], a distinction of class attributes from instance attributes (the latter are shared by all objects associated with a class, while the former represent, for example, aggregate information like an average salary only relevant to the class as a whole) [7], a unique root of the class hierarchy from which every class inherits [20], a distinction between private and public attributes [12], a different set of constructors (like one with an additional array constructor to describe matrices), an explicit inclusion of distinct types of relationships between classes and their objects (in particular various forms of composition, see [18]), integrity constraints which represent semantic information on the set of valid databases instances (a proposal in that direction appears in [3; 4], where *object constraints, class constraints*, and *database constraints* are distinguished). For another example, the ODMG-93 proposal for a standardized model [10] contains explicit keys, (binary) relationships, and inverse attributes. None of these features appear in our model, the reason being that these are *not* specific to object-orientation.

The second important aspect of an object-oriented

In combining structural and behavioral schemas, we finally obtain an *objectbase schema* of the form

$$S = (C, (T, \text{ type, isa,}), (M, P, \text{ isa, messg, impl})).$$

S is called *consistent* if the following conditions are satisfied:

(i) c isa c' implies $\text{messg}(c') \subseteq \text{messg}(c)$ for all $c, c' \in C$,

(ii) if c isa c' and $s, s' \in \text{sign}(m)$ for $m \in M$ such that $s : c \times t_1 \times \ldots \times t_n \rightarrow t$, $s' : c' \times t'_1 \times \ldots \times t'_n \rightarrow t'$, then $t_i \leq t'_i$ for each i, $1 \leq i \leq n$, and $t \leq t'$,

(iii) for each $m \in \text{messg}(c)$ there exists a $c' \in C$) s.t. c isa c' and $\text{impl}(m, c')$ is defined.

Condition (i) just says that subclasses inherit the behavior of their superclasses. Condition (ii) says that message-name overloading is done with compatible signatures, and is called the *covariance condition* in [20; 9]. The covariance condition is a significant difference from what is used at a corresponding point in programming languages, and which is known as the *contravariance* condition; for a detailed explanation, see [9]. Finally, Condition (iii) states that for each message associated with a class, its implementation must at least be available in some superclass.

It is interesting to note that various natural conditions can be imposed on the programs that are used as implementations of messages. We now sketch one of them, which is based on the view that programs are functions on domains [20]. More formally, if $m \in M$ and $s : c \times t_1 \times \ldots \times t_n \rightarrow t \in \text{sign}(m)$, then $\text{impl}(m, c)$, if defined, is a program $p \in P$ of the form

$$p : \text{dom}(c) \times \text{dom}(t_1) \times \ldots \times \text{dom}(t_n) \rightarrow \text{dom}(t)$$

The condition in question informally states that if message overloading appears in isa-related classes (so that the corresponding signatures satisfy the co-

[11] introduce distinct notions of a *method schema* to study behavioral issues of OODBS; for example, [2] investigates implications of the covariance condition using the formalism of program schemas, while [11] looks at tractability guarantees corresponding to those known for relational query languages. Also, it is pretty straightforward to define an *object algebra* for a model like the one sketched in the previous section; see, for example, the papers in [13]. That carries over to issues like query optimization, implementation of operations, and query processing. A survey of other recent investigations that have similar bases or origins can be found in [28].

We emphasize again that the model just sketched can be seen as description of the core of vastly any object-oriented model; however, this is valid only relative to the fact that many specialities, which have been proposed in the literature, or which are being built into commercial systems, are neglected here.

We conclude this section with a brief indication of how *object databases*, i.e., sets of class instances or extensions, can be defined over a given schema: For a given objectbase schema S, an *objectbase* over S is a triple $d(S) = (O, \text{inst}, \text{val})$ s.t.

(i) $O \subseteq OID$ is a finite set of object identifiers,

(ii) inst: $C \rightarrow 2^O$ is a total function satisfying the following conditions:

   (a) if $c, c' \in C$ are not (direct or indirect) subclasses of each other, then $\text{inst}(c) \cap \text{inst}(c') = \emptyset$,

   (b) if c isa c', then $\text{inst}(c) \subseteq \text{inst}(c')$,

(iii) val: $O \rightarrow V$ is a function s.t. $(\forall c \in C)\,(\forall o \in \text{inst}(c))\,\text{val}(o) \in \text{dom}(\text{type}(c))$.

Notice that this definition closes the problem left open earlier, namely that class domains originally were simply the set OID.

3 Open Issues

We next survey several modeling issues in object-oriented databases which have not yet received enough research attention:

1. *Entities can have roles that vary over time.* For example, some person object may at one point be a student, at another an employee, and at a third a club member; while the person's identity never changes, its type changes several times.

2. *Entities can have multiple types at the same time.* For example, a person may be a student, an employee, and a club member simultaneously. So far the only way to represent this in an object-oriented database is by multiple inheritance, but this might not be appropriate since it can result in a combinatorial explosion of sparsely populated classes [21].

3. *Objects can be in various stages of development.* For example, in a design environment it is usually necessary to maintain incomplete designs, i.e., objects whose types get completed in the course of time.

4. *Classes may contain "too few" instances.* For example, consider a database in which all persons living in a large country are represented. In this context, so many combinations of meaningful properties have to be distinguished that it might become necessary to introduce artificial name constructions for classes, like *unmarried-nonstudent-autoOwner-renter-taxpayer* [26], and each such class has only very few instances. More generally, the name space available for classes might not be sufficient.

5. *Objects and their classes might come into existence in reverse order.* A database user in a design environment like CAD creates objects in the first place, not type definitions or even classes. The usage of databases thus differs considerably from traditional applications where schema design has to be completed prior to instance creation.

We mention that one issue or the other from this list is sometimes reflected already in existing models, but never as a basic design target. Alternative approaches, which takes these issues into consideration right from the start, appear, for example, in [21; 24; 16]. A possible general concept for the solution of these problems seems the exploitation of prototype languages, which suggest to model applications *without* a classification that partitions the world into entity sets. A prototype represents default behavior for some concept, and new objects can re-use part of the knowledge stored in a prototype by saying how they differ from it. Upon receiving a message an object does not understand, it can forward (delegate) it to its prototype to invoke more general behavior. In the area of object-oriented programming languages, many people believe that this approach has advantages over the class-based one with inheritance, with respect to the representation of default knowledge and incrementally and dynamically modifying concepts. The investigation of *classless* models in the context of object-oriented databases has only recently been proposed in [26], and a concrete model is reported in [14].

4 Conclusions

In this short paper we have tried to give a rough personal account of recent work on formal models for object-oriented databases. Although there is not a single uniform such model, the foundations on which such models have to be built seem understood, and even standardization efforts have recently been launched [10]. On the other hand, a number of interesting research issues still deserve further investigation. In particular, formal models as they are currently available seem hardly suited for the nonstandard applications which initiated the consideration of object-orientation in the context of databases. A reason seems to be that many researchers have too much of a relational background, and try to exploit that as long as possible; this is more than confirmed by the ODMG-93 proposal. As was done a number of years ago, when database people discovered what programming-language or knowledge-representation people had been studying for years already, it seems again necessary to take recent developments in these areas into account, and to adopt them for solving the problems database applications have.

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Terminological Systems Revisited: Terminology = Schema + Views*

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Abstract

Traditionally, the core of a Termino-

relationship. This abstract architecture has been the basis for the design of systems, the development of algorithms, and the investigation of the computa-

also an Employee. Such declarations have no definitional import, they just restrict the set of possible interpretations.

The second function of a TBox is to define new concepts in terms of primitive ones by specifying necessary *and* sufficient conditions for concept membership. This can be seen as defining *abstractions* or *views* on the objects in the knowledge base. Defined concepts are important for querying the knowledge base and as left-hand sides of trigger rules. For this purpose we need more expressive languages. If cycles occur in this part they must have definitional import.

As a consequence of our analysis we propose to split the TBox into two components: one for declaring frame structures and one for defining views. By analogy to the structure of databases we call the first component the *schema* and the second the *view* part. We envision the two parts to differ with respect to the language, the form of statements, and the semantics of cycles.

The schema consists of a set of primitive concept introductions, formulated in the *schema language*, and the view part by a set of concept definitions, formulated in the *view language*. In general, the schema language will be less expressive than the view language. Since the role of statements in the schema is to restrict the interpretations we want to admit, first order semantics, which is also called descriptive semantics in this context (see Nebel 1991), is adequate for cycles occurring in the schema. For cycles in the view part, we propose to choose a semantics that defines concepts uniquely, *e.g.*, least or greatest fixpoint semantics.

The purpose of this work is not to present the full-fledged design of a new system but to explore the options that arise from the separation of TBoxes into schema and views. Among the benefits to be gained from this refinement are the following three. First, the new architecture has more parameters for improving systems, since language, form of statements, and semantics can be specified differently for ing.

2 The Refined Architecture

We start this section by a short reminder on concept languages. Then we discuss the form of statements and their semantics in the different components of a TKRS. Finally, we specify the reasoning services provided by each component and introduce different complexity measures for analyzing them.

2.1 Concept Languages

In concept languages, complex concepts (ranged over by C, D) and complex roles (ranged over by Q, R) can be built up from simpler ones using concept and role forming constructs (see Tables 1 and 2 a set of common constructs). The basic syntactic symbols are (*i*) *concept names*, which are divided into *schema names* (ranged over by A) and *view names* (ranged over by V), (*ii*) *role names* (ranged over by P), and (*iii*) *individual names* (ranged over by a, b). An *interpretation* $\mathcal{I} = (\Delta^{\mathcal{I}}, \cdot^{\mathcal{I}})$ consists of the *domain* $\Delta^{\mathcal{I}}$ and the *interpretation function* $\cdot^{\mathcal{I}}$, which maps every concept to a subset of $\Delta^{\mathcal{I}}$, every role to a subset of $\Delta^{\mathcal{I}} \times \Delta^{\mathcal{I}}$, and every individual to an element of $\Delta^{\mathcal{I}}$ such that $a^{\mathcal{I}} \neq b^{\mathcal{I}}$ for different individuals a, b (*Unique Name Assumption*). Complex concepts and roles are interpreted according to the semantics given in Tables 1 and 2, respectively.

In our architecture, there are two different concept languages in a TKRS, a *schema language* for expressing schema statements and a *view language* for formulating views and queries to the system.

2.2 The Three Components

We first focus our attention to the schema. The schema introduces concept and role names and states elementary type constraints. This can be achieved by *inclusion axioms* having one of the forms:

$$A \sqsubseteq D, \quad P \sqsubseteq A_1 \times A_2,$$

where A, A_1, A_2 are schema names, P is a role name, and D is a concept of the schema language. Intu-

Construct Name	Syntax	Semantics
top	$\top$	$\Delta^{\mathcal{I}}$
singleton set	$\{a\}$	$\{a^{\mathcal{I}}\}$
intersection	$C \sqcap D$	$C^{\mathcal{I}} \cap D^{\mathcal{I}}$
union	$C \sqcup D$	$C^{\mathcal{I}} \cup D^{\mathcal{I}}$
negation	$\neg C$	$\Delta^{\mathcal{I}} \setminus C^{\mathcal{I}}$
universal quantification	$\forall R.C$	$\{d_1 \mid \forall d_2 : (d_1, d_2) \in R^{\mathcal{I}} \rightarrow d_2 \in C^{\mathcal{I}}\}$
existential quantification	$\exists R.C$	$\{d_1 \mid \exists d_2 : (d_1, d_2) \in R^{\mathcal{I}} \wedge d_2 \in C^{\mathcal{I}}\}$
existential agreement	$\exists Q \doteq R$	$\{d_1 \mid \exists d_2.(d_1, d_2) \in Q^{\mathcal{I}} \wedge (d_1, d_2) \in R^{\mathcal{I}}\}$
number restrictions	$(\geq n\, R)$	$\{d_1 \mid \sharp\{d_2 \mid (d_1, d_2) \in R^{\mathcal{I}}\} \geq n\}$
	$(\leq n\, R)$	$\{d_1 \mid \sharp\{d_2 \mid (d_1, d_2) \in R^{\mathcal{I}}\} \leq n\}$

Table 1: Syntax and semantics of concept forming constructs.

Construct Name	Syntax	Semantics
inverse role	P^{-1}	$\{(d_1, d_2) \mid (d_2, d_1) \in P^{\mathcal{I}}\}$
role restriction	$(R{:}\, C)$	$\{(d_1, d_2) \mid (d_1, d_2) \in R^{\mathcal{I}} \wedge d_2 \in C^{\mathcal{I}}\}$
role chain	$Q \circ R$	$\{(d_1, d_3) \mid \exists d_2.(d_1, d_2) \in Q^{\mathcal{I}} \wedge (d_2, d_3) \in R^{\mathcal{I}}\}$
self	ϵ	$\{(d_1, d_1) \mid d_1 \in \Delta^{\mathcal{I}}\}$

Table 2: Syntax and semantics of role forming constructs.

schema have the role of narrowing down the models we consider possible. Therefore, they should be interpreted under descriptive semantics, *i.e.*, like in first order logic: an interpretation $\mathcal{I}$ satisfies an axiom $A \sqsubseteq D$ if $A^{\mathcal{I}} \subseteq D^{\mathcal{I}}$, and it satisfies $P \sqsubseteq A_1 \times A_2$ if $P^{\mathcal{I}} \subseteq A_1^{\mathcal{I}} \times A_2^{\mathcal{I}}$. The interpretation $\mathcal{I}$ is a model of the schema § if it satisfies all axioms in §. The problem of inferences will be dealt with in the next section.

The *view part* contains *view definitions* of the form

$$V \doteq C,$$

where V is a view name and C is a concept in the view language. Views provide abstractions by defining new classes of objects in terms of the concept and role names introduced in the schema. We refer to "$V \doteq C$" as the *definition* of V. The distinction between schema and view names is crucial for our architecture. It ensures the separation between schema and views.

A *view taxonomy* $\mathcal{V}$ is a finite set of view definitions such that (*i*) for each view name there is at most one definition, and (*ii*) each view name occurring on the right hand side of a definition has a definition in $\mathcal{V}$.

Differently from schema axioms, view definitions give necessary *and* sufficient conditions. As an example of a view, one can describe the bosses of the employee Bill as the instances of "BillsBosses $\doteq$ $\exists$boss-of.{BILL}."

Whether or not to allow cycles in view definitions is a delicate design decision. Differently from the schema, the role of cycles in the view part is to state recursive definitions. For example, if we want to describe the group of individuals that are above Bill in the hierarchy of bosses we can use the definition "BillsSuperBosses $\doteq$ BillsBosses $\sqcup$ $\exists$boss-of.BillsSuperBosses." But note that this does not yield a definition if we assume descriptive semantics because for a fixed interpretation of BILL and of the role boss-of there may be several ways to interpret BillsSuperBosses in such a way that the above equality holds. In this example, we only obtain the intended meaning if we assume least fixpoint semantics. This observation holds more generally: if cycles are intended to uniquely define concepts then descriptive semantics is not suitable. However, least or greatest fixpoint semantics or, more generally, a semantics based on the μ-calculus yield unique definitions (see Schild 1994). Unfortunately, algorithms for subsumption of views under such semantics are known only for fragments of the concept language defined in Tables 1 and 2.

In this paper, we only deal with acyclic view taxonomies. In this case, the semantics of view definitions is straightforward. An interpretation $\mathcal{I}$ satisfies the definition $V \doteq C$ if $V^{\mathcal{I}} = C^{\mathcal{I}}$, and it is a model for a view taxonomy $\mathcal{V}$ if $\mathcal{I}$ satisfies all definitions in $\mathcal{V}$.

A state of affairs in the world is described by *assertions* of the form

$$C(a), \qquad R(a, b),$$

where C and R are concept and role descriptions in the view language. Assertions of the form $A(a)$ or $P(a, b)$, where A and P are names in the schema, resemble basic facts in a database. Assertions involving complex concepts are comparable to view updates.

A *world description* $\mathcal{W}$ is a finite set of assertions. The semantics is as usual: an interpretation $\mathcal{I}$ satisfies $C(a)$ if $a^{\mathcal{I}} \in A^{\mathcal{I}}$ and it satisfies $R(a, b)$ if $(a^{\mathcal{I}}, b^{\mathcal{I}}) \in R^{\mathcal{I}}$; it is a model of $\mathcal{W}$ if it satisfies every assertion in $\mathcal{W}$.

Summarizing, a knowledge base is a triple $\Sigma = \langle \S, \mathcal{V}, \mathcal{W} \rangle$, where $\S$ is a schema, $\mathcal{V}$ a view taxonomy, and $\mathcal{W}$ a world description. An interpretation $\mathcal{I}$ is a model of a knowledge base if it is a model of all three components.

2.3 Reasoning Services

For each component, there is a prototypical reasoning service to which the other services can be reduced.

Schema Validation: Given a schema $\S$, check whether there exists a model of $\S$ that interprets every schema name as a nonempty set.

View Subsumption: Given a schema $\S$, a view taxonomy $\mathcal{V}$, and view names V_1 and V_2, check whether $V_1^{\mathcal{I}} \subseteq V_2^{\mathcal{I}}$ for every model $\mathcal{I}$ of $\S$ and $\mathcal{V}$;

because usually the schema is much bigger than the two views which are compared. Similarly, one might be interested in the world description complexity of instance checking whenever one can expect $\mathcal{W}$ to be much larger than the schema and the view part.

It is worth noticing that for every problem combined complexity, taking into account the whole input, is at least as high as the other three. For example, if the complexity of a problem is $O(|\S| \cdot |\mathcal{V}| \cdot |\mathcal{W}|)$, its combined complexity is cubic, whereas the other ones are linear. Similarly, if the complexity of a given problem is $O(|\S|^{|\mathcal{V}|})$, both its combined complexity and its view complexity are exponential, its schema complexity is polynomial, and its world description complexity is constant.

In this paper, we use combined complexity to compare the complexity of reasoning in our architecture with the traditional one. Moreover, we use [illegible] respect to $\mathcal{SL}$-schemas. We aimed at showing two results: (*i*) reasoning w.r.t. schema complexity is always tractable, (*ii*) combined complexity is not increased by the presence of terminological cycles in the schema.

In all three cases, we assume that view names are allowed in membership assertions and that the view taxonomy is acyclic. In this setting, every view name can be substituted with its definition. For this reason, from this point on, we suppose that view concepts are completely expanded. Therefore, when evaluating the complexity, we replace the size of the view part by the size of the concept representing the view.

We have found the following results for the three systems in which $\mathcal{SL}$ is the schema language and the concept language the abstraction of the query language of CONCEPTBASE introduced in [Buchheit *et al.*,1994], or the language offered by KRIS or CLASSIC, respectively.

CONCEPTBASE: instance checking is in PTIME w.r.t. combined complexity (view subsumption has been proved in PTIME in [Buchheit *et al.*,1994]).

KRIS: view subsumption and instance checking are PSPACE-complete problems w.r.t. combined complexity and PTIME problems w.r.t. schema complexity.

CLASSIC: view subsumption and instance checking are problems in PTIME w.r.t. combined complexity.

We conclude that adding (possibly cyclic) schema information does not change the complexity of reasoning within the systems taken into account.

4 Conclusion

We have proposed to replace the traditional TBox in a terminological system by two components: a schema, where primitive concepts describing frame-like structures are introduced, and a view part that contains defined concepts. We feel that this architecture reflects adequately the way terminological systems are used in most applications.

We also think that this distinction can clarify the discussion about the semantics of cycles. Given the different functionalities of the schema and view part, we propose that cycles in the schema are interpreted with descriptive semantics while for cycles in the view part a definitional semantics should be adopted.

In three case studies we have shown that the revised architecture yields a better tradeoff between expressivity and the complexity of reasoning.

The schema language we have introduced might be sufficient in many cases. Sometimes, however, one might want to impose more integrity constraints on primitive concepts than those which can be expressed in it. We see two solutions to this problem: either enrich the language and have to pay by a more costly reasoning process, or treat such constraints in a passive way by only verifying them for the objects in the knowledge base. The second alternative can be given a logical semantics in terms of epistemic operators (see Donini *et al.* 1992).

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Using Natural Language for Database Design

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Abstract.
This paper deals with a natural language dialogue tool for supporting the database design process. We want to illustrate how natural language (German) can be used for obtaining a skeleton design and for supporting the acquisition of semantics of the prospective database. The approach is based on the assumption that verbs form a central part in defining the meaning of sentences and imply semantic roles in the sentences which have to be filled by objects. We are using a moderated dialogue for drawing the designer's attention to these objects in order to extract comprehensive information about the domain.

1 Introduction

The quality of database design is a decisive factor for the efficiency of a database application. A database designer has to use a high level of abstraction for mapping his real-world application onto an entity relationship model. The designer has to learn the model and the constraints to use it.

Natural language can be exploited in order to overcome this bottleneck. From our point of view a user-friendly design system has to have two supporting tools: firstly, a tool which makes available an interface for obtaining a natural language description of an application and secondly, a tool for paraphrasing database schemes in a natural language way (see also [FloPR85]).

[ColGS83], [TseCY92], [TjoB93] are presenting various methods dealing with natural language as input for database design systems. These systems are based on natural language texts for the requirement specification in the data base design process. This paper illustrates how natural language in a dialogue tool can be used for gathering the knowledge of the designer and how it can be transfered into an extended entity relationship model

In the database design project RAD ([ThaA94]) we have implemented a rule-based dialogue design tool for getting a skeleton design on the basis of the extended entity-relationship model HERM [Tha91]. The designer describes the structure of an application in German. The specification and formalisation of semantic constraints is one of the most complex problems for the designer. Within natural language sentences the designer uses semantic constraints intuitively. For that reason, within the natural language design process we focus on extracting comprehensive semantic information about the domain from natural language utterances. The results of the dialogue are available in the internal DataDictionary for the other tools (grahical interface, integrity checker, strategy adviser,...) of the system. Within the RAD system the designer can use these results for various forms of representation, e.g. a graphical representation. The skeleton design with the semantic constraints is also the basis for further semantic checks, e.g. of key candidates, and will restrict the search areas in the checking process.

For the theoretical and pragmatic analyses of the language used within the design dialogue it was necessary to do this with a practical example. So we decided to choose the field of library - its tasks and processes. As a method of obtaining the linguistic corpus we carried out a number of interviews with librariens and library users. The extracted corpus was analysed statistically to obtain the frequency of word forms and the occurence of synonyms and homonyms. Starting from this domain we developed relations to other domains (see [BucD94]).

The dialogue tool will be implemented in PROLOG.

2 The structure of the dialogue tool

For the acquisition of designer knowledge we decided to

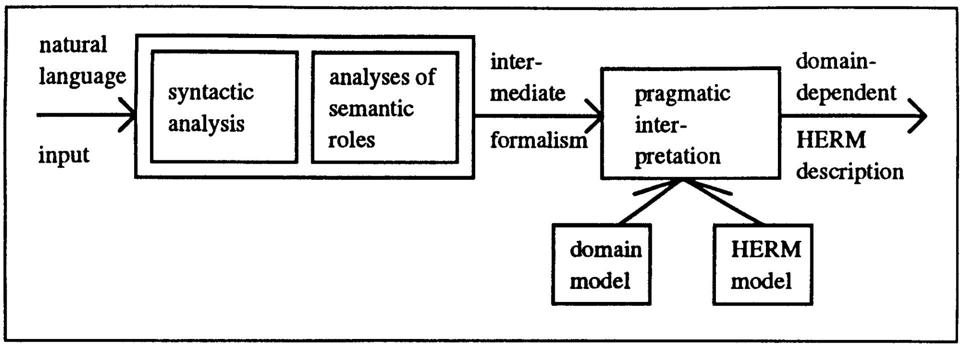

Fig. 1. Two-stage Dialogue interpretation tool

sentences. Each sentence will be analysed syntactically as well as semantically and then transformed into HERM stuctures.

Within the dialogue the results of the syntactic, semantic and pragmatic analyses will be used for controlling the dialogue. That means, if an incomplete designer input is received a question will be initiated. Inputs are incomplete if either semantic roles are not complete or the newly generated design model is incomplete. Semantic roles are filled within the semantic analysis. The pragmatics realizes the transformation of the natural language sentences into HERM structures.

2.1 Syntactic analysis

The syntactic analysis of the natural language input of the designer is based on a GPSG parser (Generalized Phrase Structure Grammar) [Gaz85]. GPSG belongs to the family of Unification Grammars. A basic feature is the introduction of ID/LP Rules (Immediate Dominance/ Linear Precedence). Immediate Dominance determines the immediate dominance of a root over its followers, Linear Precedence determines the order in which the follower, e.g. syntactic categories are to be processed.
The parser implemented in our tool uses the Earley

2.2 Semantic analysis

Interpreting the semantics of the designer input we are using the model of Bierwisch [Bie88] which inserts a semantic level between the syntax level and the conceptual level (HERM data model).

We assume that verbs form a central part in defining the meaning of sentences and the relationships between parts of sentences. Basically they describe actions, processes and states. We have tried to find a classification of verb semantics that can be applied to all verbs in the German language. Our aim was to keep the number of classes small and fairly general but large enough to identify their function in a sentence correctly. This classification (see also [BucD94]) is, at this stage, independent of the domain to be analysed (cf.Fig.2).

To identify the meaning of sentences, we have used the model of semantic roles. Verbs of a special class imply the occurence of semantic roles. The units in a sentence or an utterance are seen to fulfil certain roles. Our role concept is mainly based on the hypothesis by Jackendoff [Jac83] and consists of the following roles which refer to the objects partaking in the action: Cause, Theme, Result/ Goal, Source, Locative, Temporal, Mode, Voice/Aspect.
The following example illustrates the role concept.

Example. 'The user borrows a book with a borrowing-slip'

```
results of the semantic analysis:
verb type:    change of ownership
subject:      the user
object:       a book
locative:     ?*
temporal:     ?*
mode:         with a borrowing-slip
```

(* an additional question will be initiated)

2.3 Pragmatic interpretation

2.3.1 Obtaining a skeleton design

The transformation of the structure of natural language sentences into EER model structures is a process which is based on heuristic assumptions, e.g., we assume that all nouns are entities. [TjoB93] illustrate a large number of such heuristics in an informal way. If we accept these heuristics then we can formalize them using contextfree and contextsensitive rules.

Example.
/* all nouns are transferred into entities */
```
N(X)  → entity(NAME,X).
```

/* sentences with the main verb 'have' are transferred into an entity (the subject) and the according attribute (the object of the sentence) */

```
N(X),subject(X),V(haben),N(Y),object(Y)
   →entity(X),attre(X,Y).
```

Considering the results of the syntactic analysis of a natural language sentence we can describe these results using a tuple structure.

Example. The tuple structure of the sentence 'the user borrows a book with a borrowing-slip' is:

```
S(NP(DET(the),N(user)),
  VP(VP(V(borrows),NP(DET(a),N(book)),
                    PP(PRAEP(with),
                       NP(DET(a),
                          N(borrowing-
                             slip)))))
```

The tuple can be seen as a language which can be described by a grammar, e.g. terminals are N, DET or VP. The HERM model can also be seen as a language if predicates are used to describe the elements of the model. *Now we can handle the transformation as a compiler process using an attribute grammar.* The heuristics are integrated into grammar rules as well as into semantic rules. A compiler for this purpose has been developed. The following example illustrates how the transformation is realized.

Example. Transforming the utterance 'at the library' into an entity named 'library' using a contextfree grammar formalism. (The small letters identify nonterminals, and the capital letters are terminals. '$x' is a variable. 'assert(X)' asserts 'X' to the model description.)

tuple structure:
```
S(PP(PRAEP(at),NP(DET(a),N(library))))
```

grammar rules:
```
start → S(phrase)
phrase → PP(pp_phrase)
pp_phrase → PRAEP($x),NP(np_phrase)
np_phrase → NP(det_phrase,n_phrase)
det_phrase → DET($x)
n_phrase → N($x) {assert(entity($x))}
```

The advantage of this approach is that we can define actions at the word category level as well as at the sentence phrase level. So, it is possible to define database design actions, e.g. when considering the occurence of a genitive nominal phrase connected with another nominal phrase in the sentence. The heuristics underlying is that a genitive nominal phrase has an attribute function concerning the corresponding nominal phrase.

We are using a dialogue in which the designer can formulate a description of an application in several sentences. For that reason we have to deal with the problem of inserting a new part of a design into an existing design. We have implemented a two-step approach. Firstly, a seperate design will be generated from the sentence of the user. Secondly, the design description will be updated inserting the new design part. Common heuristics are the basis of the updating process (cf. [Düs94]).

2.3.2 Extracting information on behaviour

In most cases a database will be used for complex processes. In order to be able to maintain the database we have to define transactions. (For the reasons of using transactions see [Tha94:114].) The behaviour of the database can help to make the system more efficient and faster and thus to save time and money.

Behaviour can best be gained from a knowledge base. One form of presenting the domain is by classification of the processes involved as a conceptual graph. The knowledge base will be used for gathering relevant processes of the application and is based on the results of the semantic analysis. Each application can be classified. Lending processes are identified by verbs of the class

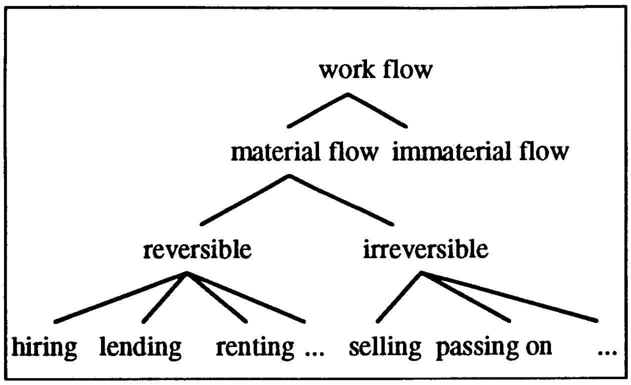

Fig. 3. Part of the process classification

'change of ownership'. The library processes or the 'rent a car' processes (cf. Fig. 3) belong to this group.

The lending process as a complex process can be further classified into a number of pre and post processes (cf. Fig. 4). These processes are included in the knowledge base. If a user input contains one of these processes a possible classification will be defined and an action within the dialogue will be initiated.The pre and post processes in Fig. 4 can be further subdivided into processes which are summarized in the above classification. Lending thus requires the processes of obtaining a user card, updating the user card if need be checking whether the book is held and available, filling in a borrowing-slip and signing it.

Example. The sentence 'the user borrows a book with borrowing-slip' implies the following general questions (borrowing has the synonym lending):

```
preprocesses:
1) Is the process 'obtaining' situated before
     'lending' ?
2) Is the process 'registration' situated
     before 'lending' ?
main processes:
3) Is the process 'document exists' situated
     before 'lending' ?
4) Is the process 'document valid' situated
     before 'lending' ?
     ...
postprocesses:
5) Is the process 'returning' situated after
     'lending' ?
```

The designer has to give correct answers.

3 Conclusions/ Future Topics

We have presented a dialogue tool consisting of a syntax analyser, a semantic role definer and a pragmatics interpreter. The dialogue tool gathers information on structure, semantics and behaviour of the prospective database. By means of transformation rules this information is mapped onto the HERM model.

The advantage of the dialogue tool is that the designer can describe the requirements of the database system in a natural language (German) and thus can specify the knowledge of a domain in a natural way. This knowledge is then employed for gathering database constructs such as entities, attributes, cardinalities, constraints, etc.

The efficiency of the database greatly depends on the exact interpretation and transformation of the natural language input analysis. The accuracy, on the other hand, depends on the size and complexity of the grammar used and the scope of the lexicon.

Work in future has to concentrate on extending the grammar to comprise all types of sentences and other hitherto excluded parts of grammar and on ways of steadily increasing the lexicon. For reasons of integrity we cannot leave updating of the lexicon to the chance designer who may have no linguistic training. Much work will have to go into completing and maintaining the linguistic background before it can finally be used for any type of systems design.

A second future topic is the application of the linguistic knowledge for acquiring further semantic information of the prospective database, e.g. acquiring key attributes or functional dependencies.

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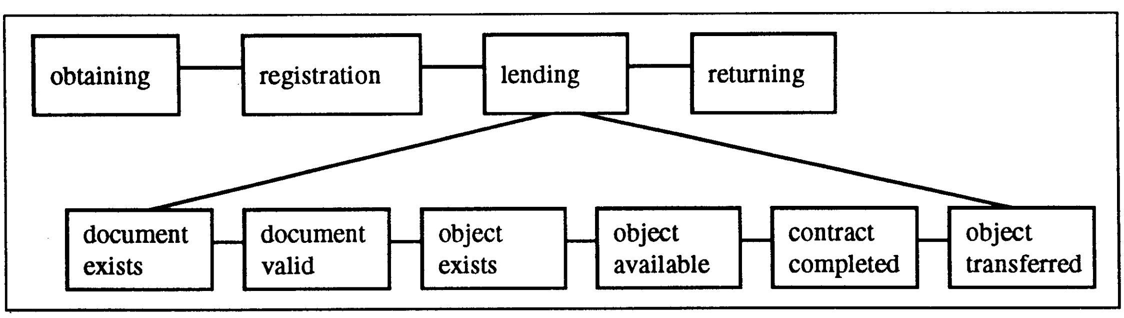

Fig. 4. Part of the knowledge base: pre, main and post processes of the act/borrowing/ lending

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What's in a Federation?
Extending Data Dictionaries with Knowledge Representation Techniques

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1. Introduction

Databases and knowledge representation languages have a rather different view upon data: knowledge representation languages describe a universe of discourse in a taxonomy and allow a user to ask epistemic questions against the relationships between concepts and roles. However, no data structures, data locations, nor any information about the existence or availability of data can be found in a taxonomy -- even not if it includes an assertion that describes a particular data item.

Relational databases provide users with schemata. Schemata describe in detail the data structures of sets of persistent data items. Data dictionaries, included in these systems, tell about data existence and its availability. Anyway, these tools do not provide the entity view, relationships between entities are merely implicit, and no question about the universe of discourse that is behind a schema will get an answer.

Object-oriented databases provide users with class hierarchies as schemata. They support the entity view -- is-a as well as part-of relationships are explicit. Nevertheless, an information about the universe of discourse is not given as well.

In a federation of systems -- databases and applications, for instance -- the situation gets worse. Databases may be heterogeneous in their modeling technique: some will follow the object-oriented the majority certainly follows the relational paradigm. How does a user get to know what data is available in a federation, if he wants to build a new application? How does that user get to know how he may access a particular data item? How does he know that the selected data item is semantically correct concerning the context of his application?

If he can access a federated data dictionary, it will provide him with the technical information about the data in a common data model -- similar to the global conceptual schema of a distributed database. If such a tool does not exist, the user must read all available schemata from all available federation components (i.e., he must know about all languages, data models, and dialects that the local components of the federation individually use).

In the remainder of this paper we will briefly introduce a module that coordinates a federation of systems and that hosts a central data dictionary. It is the module, which we will extend to provide users with an entity view upon the information available in a federation.
We introduce the logical architecture of a prototypical implementation of this module in section 2 and describe some extensions that we made in section 3. In section 4 we specify some ideas of the mentioned extension, conclude in section 5 and give some literature in section 6.

2. The Federal System Manager

The Federal System Manager (FSM) is a module that coordinates a federation of autonomous systems. These systems can be applications or services like databases, which may link to the FSM to form a federation for some particular tasks. Afterwards they can leave the federation and run again as autonomous systems. This idea is rather similar to the concept of multi-agent systems.

The FSM performs a minimum of three tasks: The first one is to run a protocol that enables the linkage process and guarantees a negotiation of autonomy aspects to the components, if these want to join or leave the federation. Second, the FSM must provide a uniform view upon all information that is available to applications of the federation through a so-called Common Data Model (CDM). Third, it must support an exchange of information, i.e., data types and data itself, between members of the federation. We will detail these tasks and concentrate on the second one.

Comparing an FSM with the Common Object Request Broker Architecture (CORBA) [1] the FSM is an object broker that looks at databases as service providing objects and applications as clients that request these services. Commonly known services from database components are storage, retrieval, update, etc.

Moreover, the FSM is an object itself! It provides services like data and type exchange. It contains a Federal Data Dictionary (FDD) that allows a user to retrieve the information contents of the actual federation under several aspects. It is our aim to extend this Federal Data Dictionary with knowledge representation techniques to better support users in their retrieval than before.

2.1. The FSM Prototype

The currently implemented FSM prototype has its roots in an ESPRIT project, finished in 1991 [2,3,4,5,6]. The prototype mainly follows the reference

available for all programs written in this programming language. Application objects described in our CDM are (under certain conditions) transformable into all data models that are represented in the FSM.

The Meta Layer

An extension of the IRD standard was made for the meta layer. If the FSM supports an exchange of data between components, it must be able to transform data between the different individual data descriptions into entities of the CDM and then -- for storage purposes -- transformed into entities of a database data model.

The entity information in CDM-format is stored in the Federal Data Dictionary (FDD) for retrieval purposes.

The Application Layer

Finally the data that comes from applications is stored in databases that have joined the federation, that are represented through meta-information in the Meta Knowledge Base, and that are willing to perform the storage process after a negotiation of their autonomy rights.

Of course, the data is not stored as CDM-typed data but is typed according to the data model of the involved database system. The interpretation of binary data runs the same way as the transformation of type information: It goes from the data model of the application towards the CDM and from the CDM to the database data model, and vv.

3. Extensions of the FSM Prototype

Since 1991 the FSM prototype has been completed by some student's work.

The Federal Data Dictionary of the prototype contained information about data type declarations, the types of application entities, and the structure of these entities -- as well, access rights were included. It did not include any technical information about the availability of entities or schemata.

We extended the FDD and it now contains technical information about the federation components. The meta layer includes information about the technical system that hosts the application or the database system. The schema layer includes information about the technical availability of entities [9].

The lack of a docking mechanism and a protocol to negotiate autonomy was another problem of the original FSM prototype. It was a static system with two applications, a database system and the FSM with hard wired mechanisms to read data type declarations -- database schemata could not be read, nor was it possible to link another database system with the FSM.

Now we have implemented a link mechanism that generalizes the old one [10]. We now use a FSM-Bind module that binds a component -- either a database system or an application -- if it includes our FSM-Bind-Agent.

The FSM-Bind-Agent acts as a client to the FSM-Bind module, which is the server, and performs the link process between FSM and component. It runs an implemented protocol for start-up and shut-down situations and uses the Remote Procedure Call (RPC) technique.

After linkage the FSM-Bind-Agent passes control to a so-called FSM-Agent, which performs the information exchange and the retrieval of schema information via the Remote Data Access (RDA) protocol.

What is still missing, is a user friendly retrieval facility that completes the Federal Data Dictionary. We will describe our ideas in the next section.

3.1. Extensions of the FDD

Data dictionaries offer technical information to users -- and exactly this can be expected from our Federal Data Dictionary as it is currently implemented. If a user wants to build a new application he looks into the FDD and looks up some data structures that he wants to re-use. Then he includes the chosen data structures into his new schema (the FSM provides some commands to do so) and runs his application.

This user is unable to check whether his new schema violates the semantic integrity of the universe of discourse of the actual federation because he can not ask the FDD to present him semantic relations between entities.

We wish to provide such a user with an extended Federal Data Dictionary, which shows the contents of a federation from various levels of abstraction. If this extended data dictionary has a graphic interface the user will use a mouse to easily request the change of levels. Which are these levels?

Taxonomy Level

The highest level presented, should be a taxonomy upon the universe of discourse. It could be the union of all schemata (and may be data type declarations of applications) of local database components, which we previously transformed into the abstraction level of a concept language. This level would represent the data of a particular federation without any technical details. Here the user could look-up the real-world context of an entity and might ask questions about the relationships between entities. It is the level that KL-ONE like languages usually offer to users with their T-Box.

Concept Languages separate between the terminological (T-Box) and assertion knowledge (A-Box). The task, which we have to perform is to abstract the technical information from schemata and data type declarations to concepts of concept languages. In [11] we find a theoretical basis that allows us to express database schemata with concept languages.

Moreover, the authors show that classification is then available for entities of schemata -- and we found out that the implementation of a classificator is surprisingly supported through an algorithm, which we use within the FSM to detect data type intersections for types from different data models. This algorithm follows perfectly the above mentioned steps for a classification of concepts.

Anyway, if we make the is-a and part-of relations of entities from schemata explicit and suppress the technical information, then we can ask questions against a schema similar to the questions against a taxonomy.

The implementation of this level may use intermediate language representations that follow the idea of attributed trees. This model allows us to determine the degree of entity detail information, which we want to present, by cutting the tree at a certain level. The information above the cut is presented as concept. The

We realize this view by an FDD retrieval, because our directory includes the structure information of entities in a neutral representation and the information about the availability of these entities.

Syntax Level

Finally, the user may get what he always got from databases: the pure schema information. If he asks for this, he will get an excerpt of a schema of one or more particular local components of the federation -- and he should decide himself whether he would like to receive this information in the format of a common data model or in the individual format of the involved local federation components.

4. First Steps toward the Taxonomy Level

Concerning the integration of abstract schema representations into one taxonomy we did some work in advance and evaluated an idea, published in [12]. It proposed the assignment of fuzzy values to however, gave a new balance to both values, which

according to the new schema. The first case, C_1, was used if a relationship was found in a schema -- it corresponds with the INIT function for the taxonomy -- and set C_S (E_i, E_j) := 1. We assume that the designer of the schema did a good and correct work.

The second case, C_2, was used, if we find a relationship within the schema but not within the taxonomy. We insert the relationship into the

A second test gave surprising results: We inserted the two C-type schemata and then four times the A-type schemata. This gave a high value to the "B is-a C" relationship first -- the balance was 0.5 for "B is-a A" and 0.84 for "B is-a C" -- and a final value of 0.96 for "B is-a A" and 0.37 for "B is-a C".

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Do we need the closed-world assumption in knowledge representation?

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1 Introduction

Database systems and knowledge representation systems represent and reason about some aspect of the real world. In both it is common to separate the two functions of *representation*, i.e. describing the conceptual scheme and the actual data, and *computation*, i.e. answering of queries and manipulation of data.

The database management system of a database system provides a data definition language to describe the conceptual scheme. The data definition language is used to describe the database in terms of a data model. Operations on the database require a specialized language, called a data manipulation language or query language. One of the most important data models is the *relational model* which describes the world in terms of atomic values and relations on the set of all atomic values. Data manipulation languages of the relational model comprise the relational algebra, and the domain and tuple relational calculi. The *object-oriented model* supports a more elaborated description of the world by allowing complex objects, i.e. objects constructed using typically used in the construction of the knowledge base of a reasoning agent. A knowledge base can be thought of as representing the beliefs of such an agent. One of the most prominent knowledge representation formalisms is KL-ONE [Brachman and Schmolze,1985] which has been used in the construction of natural language processing systems.

The knowledge representation language of KL-ONE and all it's derivates can be considered as a subset of first-order logic with equality. With respect to describing structural properties of objects and conceptual schemes they are more expressive than the data definition languages corresponding to the relational or object-oriented model.

In the late eighties inference in KL-ONE was shown to be undecidable [Schmidt-Schauss,1989]. Since then the emphasis in research has been on developing and investigating systems that are computationally well behaved, i.e. are tractable or at least decidable [Brachman *et al.*,1991; Donini *et al.*,1991; Buchheit *et al.*,1993]. As a result many commonly used knowledge representation languages have restricted expressiveness and are in their current form no longer suitable for natural language applications

In the next section I will give some examples that show the usefulness of closed-world inferences in natural language processing. Thus knowledge representation languages sticking to the open-world assumption seem to be insufficient for natural language processing.

2 Query answering in Natural Language Processing

In cooperation with the PRACMA Project[1] (Department of Computer Science, University of Saarbrücken) we have been developing a suitably extended knowledge representation system, called MOTEL [Hustadt and Nonnengart,1993], which is intended to be a module of the PRACMA system. The PRACMA Project [Jameson *et al.*,1994] is concerned with the modeling of noncooperative information-providing dialogues. An example from PRACMA's domain is the dialogue between a person $\mathcal{S}$ trying to sell her used car to a potential buyer $\mathcal{B}$. Naturally, the goals of $\mathcal{S}$ conflict in part with those of $\mathcal{B}$.

In the final implementation, the natural language analysis module of the PRACMA system will use the semantic representation language $\mathcal{NLL}$ [Laubsch and Nerbonne,1991] to represent the German-language input strings. The resulting $\mathcal{NLL}$ expressions will be stored in the pragmatic dialogue memory. Various modules will process the content of the dialogue memory, the most important one for us is the *comment and question handler*. The result of this module is transfered to the natural language generator which is responsible for verbalizing $\mathcal{NLL}$ expressions.

$\mathcal{NLL}$ contains a first-order logic core with anadic predicates, generalized quantifiers, plural reference expressions, and λ-abstraction. To fit the purposes of PRACMA the language has been extended by modal operators.

Suppose the knowledge base of the car seller $\mathcal{S}$ contains declarations defining that vehicles are either cars or trucks, **veh1** is a truck, and **veh2** is a vehicle. This can be represented in $\mathcal{NLL}$ in the following way.

```
(forall ?x vehicle(inst: ?x) iff
        (car(inst: ?x) or
         truck(inst: ?x))                  (1)
truck(inst: veh1)                          (2)
vehicle(inst: veh2)                        (3)
```

Here **veh1** and **veh2** are constants, **vehicle**, **car**, and **truck** are predicate symbols. In $\mathcal{NLL}$ arguments of predicates are identified via keywords, e.g. **inst**, rather than positions in argument vectors. Any identifier preceded by a question mark, e.g. **?x**, is a variable. In addition we have used the boolean operators **iff** (equivalence) and **or** (disjunction), and the universal quantifier **forall** in declaration (1).

Now a question of the buyer concerning which objects are either cars or trucks is represented in the following way.

```
(?lambda ?x car(inst: ?x) or
         truck(inst: ?x))                  (4)
```

An expression of the **(?lambda ?x** P**)** denotes the set of all **?x** satisfying P. The answer we have to infer from the knowledge base is that **veh1** and **veh2** both belong to this set.

Obviously, this answer cannot be computed by the comment and question handler without taking declaration (1) into account. For instance, it is not possible to find the correct answer to (4) by computing the answer sets for **(?lambda ?x car(inst: ?x))** and **(?lambda ?x truck(inst: ?x))** and to return the union of the resulting sets as an answer.

A question of the buyer concerning which objects do not belong to the set of trucks is translated into the following $\mathcal{NLL}$ expression.

```
(?lambda ?x not car(inst: ?x))             (5)
```

Whereas the closed-world assumption would allow us to infer that **veh1** belongs to this set, the open-world assumption underlying $\mathcal{NLL}$ doesn't support this conclusion.

The question whether all cars are vehicles can also be formulated in $\mathcal{NLL}$. To answer this question we can try to infer

```
(forall ?x vehicle(inst: ?x) if
        car(inst: ?x))                     (6)
```

from the knowledge base. The answer to this question has to be independent of the constants currently occurring in our knowledge base. On the basis of declaration (1), the answer has to be positive.

Now let us assume that the left front seat of **veh2** is red. Choosing **lfseat** to designate the left front seat, this can be represented in the following way.

```
hasPart(inst: veh2, theme: lfseat)         (7)
seat(inst: lfseat)                         (8)
hasColour(inst: lfseat, theme: red)        (9)
```

To answer the question whether all seats of **veh2** are red we have to try to infer the following $\mathcal{NLL}$ expression.

```
(forall ?x
    hasColour(inst: ?x, theme: red)
    if hasPart(inst: veh2, theme: ?x)
       and seat(inst: ?x))                 (10)
```

Because of the open-domain and open-world assumption, the answer to the question cannot be positive. Although the only seat the car seller knows to be part of **veh2** is actually red, there may be other seats of **veh2** and these seats may not be red.

Intuitively, a positive answer is much more plausible. We would assume that the car seller knows all the seats of **veh2** and knows the colour of every seat of **veh2**. It is possible to extend the knowledge base using *number restrictions* in such a way that we can infer a positive answer, e.g.

```
((= 1) ?x hasPart(inst: veh2, theme: ?x)
       and seat(inst: ?x))                 (11)
```

[1]PRACMA is short for 'PRocessing Arguments between Controversially Minded Agents.'

declares that veh2 has exactly one seat. declarations (7),(8),(9), and (11) taken together allow us to answer query (10) positively. However, it seems to be more natural to extend the language by an *epistemic modal operator* in the style of Lifschitz [Lifschitz,1991] to solve the problem. For a description of an extension of the knowledge representation language $\mathcal{ALC}$ by an epistemic operator refer to Donini et al. [Donini *et al.*,1992].

Suppose our language contains such an epistemic operator K. Then we have two possibilities to get a positive answer to the question. The first possibility is to reformulate the question slightly in the following way.

```
(forall ?x
    hasColour(inst: ?x, theme: red) if
    K(hasPart(inst: veh2, theme: ?x)
      and seat(inst: ?x)))                  (12)
```

Now the question is whether all known seats of veh2 are red and the answer has to be positive. This approach causes the problem how the natural language analysis module should determine the epistemic character of question (12) opposed to the non-

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Tractable Reasoning in a Universal Description Logic: Extended Abstract*

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1 Introduction

Description logics (also called *terminological logics* or *concept languages*) have been designed for the logical reconstruction and specification of knowledge representation systems descending from KL-ONE such as BACK, CLASSIC, $\mathcal{KRIS}$, and LOOM.[1] These systems are used to make the terminology of an application domain explicit and then to classify these definitions automatically into a taxonomy according to semantic relations like subsumption and equivalence. More precisely, automatic classification refers to the ability to insert a new concept into the taxonomy in such a way that it is directly linked to the most specific concept it is subsumed by and to the most general concept it in turn subsumes. Terminological knowledge representation systems thereby support the task to formalize an application in at least two respects. On the one hand, they urge the user to isolate the intrinsic concepts of the application; on the other hand they may detect hidden subsumption and equivalence relations between definitions or may even detect that a definition is incoherent.

A model of the application is then given by associating special objects of the domain with the concepts of the terminology. The systems mentioned above in turn automatically classify these objects with respect to the given terminology and to those membership relations which have been asserted explicitly. In this case, however, automatic classification refers to the ability to find the most specific concept the object is a member of.

Terminologies comprise two different kinds of terms, viz. so-called *concepts* and *roles*. The former are intended to represent classes of objects of a given domain, while the latter represent binary relations over this domain. Concepts can either be simple *concept names*, representing not further specified classes of objects, or structured by means of a fixed set of *concept structuring primitives*. Common concept structuring primitives are *concept conjunction* $\sqcap$ and universal quantification $\forall R{:}C$ over a role R. Concept conjunction is to be interpreted as set intersection, while the concept $\forall R{:}C$ denotes all those objects d of the domain for which each object related to d by the role R is a member of the concept C. Although there exist many other concept structuring primitives, it is commonly accepted that these two should be part of each concept language. In contrast to concepts, roles are often taken to be atomic, i.e., there are no roles other than *role names*. The standard concept language $\mathcal{ALC}$, for instance, does not comprise any role structuring primitives. However, in addition to those mentioned above, this language comprises *concept disjunction* $\sqcup$, *concept negation* $\neg$ as well as existential quantification $\exists R{:}C$ over a role R as concept structuring primitives. For details the reader is referred to [Schmidt-Schauß and Smolka, 1991].

Definitions are given by associating a concept or role T with a concept name (resp., role name) TN. Such a definition is represented by the expression $TN \doteq T$ and is called *concept* and *role introduction* respectively. *Terminologies* are just finite sets of concept and role introductions such that each concept and role name is defined at most once, i.e., for every concept and role name TN there exists at most one concept or role introduction the left-hand side of which is TN.

As already mentioned, a model of application domain is described in terms of the given terminology. More precisely, specific objects of the domain and pairs of objects can be associated with concepts and roles of the terminology, where these objects are syntactically represented by so-called *individual names*. It can either be asserted that an individual name a is an instance of a concept C or that it is related to another individual name, say, b, by a role R. Such assertions are called *assertional axioms* and are represented by the expressions $a{:}C$ and $(a, b){:}R$ respectively. A finite set of assertional axioms forms a *knowledge base*.

From a theoretical point of view, the computational service provided by terminological knowledge representation systems can be reduced to answer queries of the following form with respect to a knowledge base $\mathcal{KB}$ and to a terminology $\mathcal{T}$: a *query* can be an assertional axiom or an *inclusion axiom* of the form $T_1 \sqsubseteq T_2$, where T_1 and T_2 are either two concepts or two roles. The meaning of such a query Q posed with respect to $\mathcal{KB}$ and $\mathcal{T}$ is usually given in terms of so-called interpretations and models. An *interpretation* $\mathcal{I}$ consists of a *domain* $\Delta^{\mathcal{I}}$ and a *val-*

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[1] For a good overview of the so-called KL-ONE family the reader is referred to [Woods and Schmolze, 1992]; for KL-ONE itself cf. [Brachman and Schmolze, 1985].

uation $\mathcal{V}$ over $\Delta^{\mathcal{I}}$ along with an *interpretation function* $.^{\mathcal{I}}$. The valuation $\mathcal{V}$ over $\Delta^{\mathcal{I}}$ maps each concept name to a subset of $\Delta^{\mathcal{I}}$ and each role name to a binary relation over $\Delta^{\mathcal{I}}$. Individual names, however, are mapped to singleton sets containing exactly one element of $\Delta^{\mathcal{I}}$. The interpretation function $.^{\mathcal{I}}$, on the other hand, just extends $\mathcal{V}$ to deal with arbitrary concepts and roles in such a way that all concept and role structuring primitives are interpreted properly. The concept structuring primitives $\sqcap$, $\sqcup$, $\neg$, for instance, are to be interpreted as the corresponding set operations on $\Delta^{\mathcal{I}}$, while the interpretation of the concept $\forall R{:}C$ is defined inductively as follows: if $C^{\mathcal{I}}$ and $R^{\mathcal{I}}$ have already been defined, then $(\forall R{:}C)^{\mathcal{I}}$ is $\{d \in \Delta^{\mathcal{I}} : \forall e(\langle d,e\rangle \in R^{\mathcal{I}}), e \in C^{\mathcal{I}}\}$.

An interpretation $\mathcal{I}$ is then said to be a *model* of the inclusion axiom $T_1 \sqsubseteq T_2$ just in case that $T_1^{\mathcal{I}} \subseteq T_2^{\mathcal{I}}$ and, if a and b are individual names such that $a^{\mathcal{I}}$ is $\{\underline{a}\}$ and $b^{\mathcal{I}}$ is $\{\underline{b}\}$, then $\mathcal{I}$ is a model of the assertional axiom $a{:}C$ (resp., of $(a,b){:}R$) just in case that $\underline{a} \in C^{\mathcal{I}}$ (resp., $\langle \underline{a}, \underline{b}\rangle \in R^{\mathcal{I}}$). Not very surprising, an interpretation is a *model* of $\mathcal{KB}$ and $\mathcal{T}$ if it is a model of each of the elements of $\mathcal{KB}$ and $\mathcal{T}$. Now, Q is said to be *entailed* by $\mathcal{KB}$ and $\mathcal{T}$, written $\mathcal{KB} \models_{\mathcal{T}} Q$, if and only if every interpretation which is a model of $\mathcal{KB}$ and $\mathcal{T}$ is a model of Q as well. Moreover, we say that T_2 *subsumes* T_1 with respect to $\mathcal{T}$ if and only if it holds that $\emptyset \models_{\mathcal{T}} T_1 \sqsubseteq T_2$.

2 Terminological Reasoning is Inherently Intractable

Unfortunately, answering such queries is in most cases provably intractable, at least in terms of computational worst case complexity. This applies, for instance, to the basic inference of KL-ONE, although originally claimed to be computationally tractable. In fact, Schmidt-Schauß [1989] proved that there exists no algorithm at all which decides whether one concept of KL-ONE subsumes another one or not, even with respect to empty terminologies.

Moreover, in [Schild, 1993, 94a], , it is proved that in case of the standard concept language $\mathcal{ALC}$, every

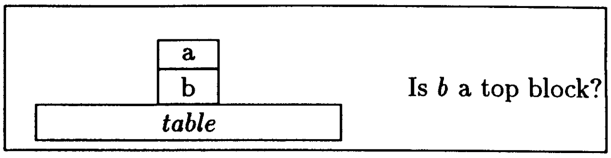

Figure 1: A sample blocks world.

$$\left\{\begin{array}{l} \forall x.block(x) \Leftrightarrow x = a \lor x = b, \\ a \neq b, a \neq table, b \neq table, \\ \forall x \forall y.on(x,y) \;\Leftrightarrow\; (x = a \land y = b) \\ \qquad\qquad\qquad\;\; \lor\;\; (x = b \land y = table) \end{array}\right\}$$
$$\overset{?}{\models} block(b) \land \neg\exists x.block(x) \land on(x,b)$$

Figure 2: Representing the sample blocks world by first-order formulae.

3 Model Checking Versus Theorem Proving

In the previous section, we have seen that, as Woods and Schmolze [1992] put it, "the surfeit of intractability results seems to have reached its logical end with the conclusion that practically everything of any use is intractable (in the worst case)." Recently, Halpern and Vardi [1991] proposed a possible solution to this very problem of knowledge representation. As a starting point, they re-examined the traditional approach to knowledge representation, going back to McCarthy [1968]. According to this approach the world to be modeled should be represented by a finite set of formulae of some given logic, preferably first-order logic. If a question to be answered is then formulated within the same logic, the answer depends on whether this formula is a *logical consequence* of the collection of formulae representing the world or not. In other words, it is checked whether *every* semantic structure which is a model of each of the formulae representing the world is also a model of formula corresponding to the question.

We shall illustrate this traditional approach to knowledge representation by means of an example, drawn from the famous blocks world. Suppose, for instance, we would like to represent a blocks world involving two blocks—say *a* and *b*, where *a* lies on *b*

$$\begin{array}{lcl} \mathcal{D}om & = & \{a, b, table\} \\ [\![block]\!] & = & \{a, b\} \\ [\![on]\!] & = & \{\langle a, b\rangle, \langle b, table\rangle\} \end{array}$$

$$\overset{?}{\models} \; block(b) \wedge \neg\exists x.block(x) \wedge on(x, b)$$

Figure 3: Representing the sample blocks world by a semantic structure.

$$\left\{ \begin{array}{l} a{:}Block, b{:}Block, table{:}\neg Block, \\ (a, b){:}on, (b, table){:}on, \\ a{:}(\neg\exists on^{-1}{:}Block), table{:}(\neg\exists on{:}Block) \end{array} \right\}$$

$$\mathcal{T} = \{ TopBlock \doteq Block \sqcap \neg\exists on^{-1}{:}Block \}$$

$$\overset{?}{\models_{\mathcal{T}}} \; b{:}TopBlock$$

Figure 4: Representing the sample blocks world by an $\mathcal{ALC}^{-1}$-KB.

$$\begin{array}{lcl} \mathcal{D}om & = & \{a, b, table\} \\ [\![Block]\!] & = & \{a, b\} \\ [\![on]\!] & = & \{\langle a, b\rangle, \langle b, table\rangle\} \end{array}$$

$$\mathcal{T} = \{ TopBlock \doteq Block \sqcap \neg\exists on^{-1}{:}Block \}$$

$$\overset{?}{\models_{\mathcal{T}}} \; b{:}TopBlock$$

Figure 5: Representing the sample blocks world by a physical $\mathcal{ALC}^{-1}$-KB.

in many cases the natural representation of a world to be modeled is a *semantic structure* rather than a collection of formulae. If, as in the traditional approach, queries are represented by formulae of a given logic, a query can be answered in this case depending on whether the formula representing the query is true in the *given* semantic structure or not. That is to say, it is checked whether the semantic structure is a model of the formula corresponding to the query. The fact that a (closed) formula α is true in a semantic structure $\mathcal{M}$ is usually indicated by $\mathcal{M} \models \alpha$. Resorting to this convention, Figure 3 gives such an alternative representation of the blocks world considered above.

In many cases this model checking approach has tremendous benefits, at least in terms of computational complexity. For instance, checking the truth of an arbitrary closed first-order formula[2] α in a finite semantic structure fixing the interpretation of all predicates and constants occurring in α is known to be *decidable* using at most polynomial space [Chandra and Merlin, 1977]. Recall that in contrast to this, there exists no algorithm at all which is able to decide whether an arbitrary formula of this kind is a logical consequence of a finite set of first-order formulae, even with only finite interpretation domains taken into account. However, it is also known that first-order model checking is still at least as hard as *any other* problem solvable using at most polynomial space, hence this problem is still very hard [Chandra and Merlin, 1977]. Anyway, Halpern and Vardi's intention was to forge a new approach to knowledge representation rather than to give concrete instances which allow for tractable inferences.

4 The Model Checking Approach to Terminological Reasoning

It should be clear that terminological knowledge representation, as described in the introduction, is committed to the traditional approach to knowledge representation rather than to the model checking approach. In [Schild, 1994b] we investigated the consequences of adapting Halpern and Vardi's model checking approach to terminological reasoning. It turned out that even in case of the most powerful description logic considered in the literature, answering queries become tractable just by replacing the usual kind of knowledge bases with single finite semantic structures fixing the interpretation of all *primitive* concepts and roles (i.e., those concept and role names which are mentioned somewhere in the terminology or in the query, but which are not defined).

But before engaging into details, have a look at Figure 4, which shows how to represent the already familiar blocks world in terms of $\mathcal{ALC}$ together with the inverse of roles $^{-1}$, as it would be done traditionally. Observe, however, that this representation is *incomplete* in that it solely states that block a lies on block b, while the latter in turn lies on the table, but it is left open whether there is any other block lying on b or on the table. As a matter of fact, there is no way at all to give an *accurate* representation of our blocks world in terms of $\mathcal{ALC}$, even when augmented by the inverse of roles. This means, in this case the so-called *open world assumption*,[3] traditionally made for terminological reasoning, is a nuisance rather than an advantage.

Figure 5 modifies the just considered representation in the spirit of the model checking approach. A finite semantic structure is shown there which fixes the interpretation of each primitive concept and role of $\mathcal{T}$, that is, it fixes the interpretation of *Block* and *on*. Such a semantic structure is obviously nothing but a valuation along with a domain. When taken together with a domain, the syntactic representation of such a valuation is called *physical knowledge base*, emphasizing the fact that they are intended to replace customary knowledge bases. Now, suppose $\mathcal{V}$ is such a physical knowledge base with domain $\mathcal{D}om$, $\mathcal{T}$ is an arbitrary terminology, and Q is a query. Then $\mathcal{V} \models_{\mathcal{T}} Q$ is intended to mean that every interpretation extending $\mathcal{V}$ which is a model of $\mathcal{T}$ is a model of Q as well, where an interpretation $\mathcal{I}$ is said to *extend* a physical knowledge base $\mathcal{V}$ with domain $\mathcal{D}om$ just in case that $\Delta^{\mathcal{I}} = \mathcal{D}om$ and, moreover, $\cdot^{\mathcal{I}}$ interprets all those concept and role names handled

[2]This formula should involve no function symbols other than constants.

[3]In contrast to the *closed world assumption*, usually made for databases, the open world assumption does *not* assume that all those facts that are not explicitly mentioned (or that cannot be inferred) are taken to be false.

by $\mathcal{V}$ in exactly the same way as $\mathcal{V}$ does.

In [Schild, 1994b] we investigated the computational complexity of answering such queries with respect to physical knowledge bases in the description logic $\mathcal{U}$, introduced by Patel-Schneider [1987] as a universal description logic. This concept language is *universal* in the sense that it encompasses all others considered in the literature, except for those which comprise nonstandard facilities like defaults, for instance. In addition to those of $\mathcal{ALC}$, this language comprises *number restrictions* of the form $\exists^{\geq n} R{:}C$ and $\exists^{\leq m} R{:}C$ as well as *role value maps* of the form $R \leq S$ as concept structuring primitives. Number restrictions restrict the number of role fillers (i.e., those objects which are related to an object by a role), while role value maps impose restrictions on the fillers of two roles. The concept $R \leq S$ states that all fillers of the role R are also fillers of the role S. In addition, $\mathcal{U}$ admits of individual names to occurring in concepts. The role structuring primitives of $\mathcal{U}$ are the *identity role* ϵ, Boolean operations $\sqcap$, $\sqcup$, $\neg$ on roles, the inverse R^{-1} of a role, the composition $R \circ S$ of two roles, as well as the *transitive closure* R^{+} and the *reflexive-transitive closure* R^{*} of a role. For details cf. [Schild, 1994b] or [Patel-Schneider, 1987]. Notably, it is known that there cannot exist any algorithm which is capable of deciding subsumption between two concepts (or two roles) of $\mathcal{U}$, even with respect to empty terminologies [Schild, 1988].

The main result of [Schild, 1994b] is that even in this language $\mathcal{V} \models_{\mathcal{T}} Q$ can be decided in polynomial time provided that each of the following conditions is satisfied:

(a) $\mathcal{V}$ has a finite domain and specifies all concept and role names occurring in $\mathcal{T}$ and Q except for those which are defined in $\mathcal{T}$;

(b) Roles are not defined recursively;

(c) Concepts can be defined recursively, but then they must occur in their definition[4] *positively*,

the concept and role structuring primitives of $\mathcal{U}$, storing already evaluated ones. To deal with recursive concept definitions, however, we exploited a technique for computing least and greatest fixed points due to Emerson and Lei [1986].

It turned out that even when relaxing condition (a) in such a way that $\mathcal{V}$ is solely required to have a finite domain, $\mathcal{V} \models_{\mathcal{T}} Q$ is still decidable in the universal description logic $\mathcal{U}$. In fact, we proved that in this case the computational complexity is essentially the same as the one of deciding ordinary subsumption between two concepts with respect to acyclic terminologies in the *minimal* concept language.[5]

We also investigated the consequences of incorporating some limited kind of incomplete knowledge by means of Reiter's *null values* [Reiter, 1984]. It turned out that, when presupposing P $\neq$ NP, admitting of null values causes intractability, even in case of $\mathcal{ALC}$. Thus our results suggest that the main source of computational complexity of terminological reasoning seems to be the ability to express *incomplete* knowledge.

5 Description Logics as Tractable Query Languages for Databases

Another interpretation of our results is that, when taken together with the least and greatest fixed point semantics, the universal concept language $\mathcal{U}$ can serve as a powerful but tractable query language for relational databases comprising solely unary and binary relations.[6] From this point of view terminologies are to be thought of as defining so-called *views*, possibly defined recursively.

At this very point, it is important to note that the universal description logic $\mathcal{U}$ is so strong in expressive power that it is even capable of *accurately* defining concepts such as directed acyclic graphs (DAGs), trees, or binary trees. The powerful role forming primitives of $\mathcal{U}$ actually admit of plausible and non-

$$
\begin{array}{rcl}
\mathit{DirectedGraph} & \doteq & \forall \mathit{connected}{:}\, \mathit{Vertex} \\
\mathit{connected} & \doteq & (\mathit{edge} \sqcup \mathit{edge}^{-1})^{*} \\
\mathit{Acyclic} & \doteq & \forall \mathit{connected}{:}(\mathit{edge}^{+} \leq \neg\epsilon) \\
\mathit{DAG} & \doteq & \mathit{DirectedGraph} \sqcap \mathit{Acyclic} \\
\mathit{Tree} & \doteq & \mathit{DAG} \\
 & \sqcap & \forall \mathit{edge}^{*}{:}\exists^{\leq 1} \mathit{edge}^{-1}{:}\, \mathit{Vertex} \\
\mathit{BinaryTree} & \doteq & \mathit{Tree} \\
 & \sqcap & \forall \mathit{edge}^{*}{:}\exists^{\leq 2} \mathit{edge}{:}\, \mathit{Vertex} \\
\mathit{AndOrGraph} & \doteq & \mathit{DirectedGraph} \\
 & \sqcap & \forall \mathit{connected}{:}\mathit{AndOrVertex} \\
\mathit{AndOrVertex} & \doteq & \mathit{AndVertex} \sqcap \neg \mathit{OrVertex} \\
 & \sqcup & \mathit{OrVertex} \sqcap \neg \mathit{AndVertex} \\
\mathit{Solvable} & \doteq & \neg\exists \mathit{edge}{:}\, \mathit{Vertex} \\
 & \sqcup & \mathit{AndVertex} \sqcap \forall \mathit{edge}{:}\mathit{Solvable} \\
 & \sqcup & \mathit{OrVertex} \sqcap \exists \mathit{edge}{:}\mathit{Solvable}
\end{array}
$$

Figure 6: A terminology of $\mathcal{U}$.

ing approach to terminological knowledge representation does make it possible to answer queries in polynomial time, there are actually nontrivial inferences to perform.

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Generating queries from complex type definitions*

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Abstract

Many information systems are implemented as application programs connected to a database system. A characteristic problem of such systems is the famous impedance mismatch, i.e., the conceptual distance between the programming and the database languages. The traditional solution is to implement an interface that transforms one representation into the other. Commercial database systems offer preprocessors that allow to embed the database language (e.g., SQL) into the programming language (e.g., C). Such an approach frees the application programmer from the task to specify details of the communication. However, the impedance mismatch is not solved but aggravated. The set-oriented database language is intermixed with the element-oriented programming language, a notorious cause for programming errors. Moreover, there is no support in mapping the restricted data representation of databases into the more complex type system of programming language. This paper proposes an intermediate language, the API modules, for specifying the relationship between the representations in the database and in the application program. The query for retrieving the information and the data types for storing it can be generated from the API module. The modules are simple enough to allow reasoning on queries generated from them.

1 Introduction

The purpose of a database system is to maintain a large amount of information for a variety of application programs. The application-specific clustering is either described as a database view definition or

case of relational databases, only flat relations can be expressed. In the case of object-oriented databases, the type system depends on the specific data model of the database system.

- Handcoded clustering by filter procedures within the application program is error-prone and gives away the chance of reasoning on the relationship between the information in the database and in the application program.

Section 2 introduces *API modules* as the interface between the database and the application program. Base types are imported from the database. Application specific types are defined by using tuple, set, and pointer constructors. The latter allows to represent recursive concepts of the database schema.

Section 3 presents the mapping of the API modules to a logic program delivering complex terms. These terms are read by a parser that itself is generated from the API modules.

Section 4 relates the types in an API module to statements of a concept language. Thereby, types of two different API modules can be checked for subsumption and consistency.

2 Interface Modules

Interfaces between imperative-style programming languages should both reflect the major type constructors and the facilities of the database query language. The most common type constructors are *tuple* and *set*. Some languages also support *lists*. Pseudo-recursive type definitions are possible when allowing pointer types, e.g. in C and Modula-2. Common base types are *Integer* and *String*. The denotational semantics of a type expression is a potentially infinite set of values, for example *[Integer,String]* denotes the cartesian product of the semantics of the component types.

2.1 Example

Assume a database provides information about a

```
API-MODULE Emps;
FROM CompanyDb IMPORT Employee, Project,
     Department, String;
TYPE
     EmpType/Employee = [name: String;
                         project: {Project};
                         dept: DeptType];

     DeptType/Department = [deptName: String;
                            head: *EmpType];
PORT
     e: {EmpType| dept.deptName=$N};
END.
```

Figure 1: API module for the company example

data structures on top of the imported concepts. **EmpType** is a record type which represents the name of an employee, his projects, and the department. The latter is given by the name and the reference (pointer) to that employee who is the head of the department. The purpose of the pointer is to encode recursive type definitions. The PORT declaration defines which information of the database should be teransfered to the application program. Here, all employees who have a department named by **$N** are of interest. The token **$N** denotes a placeholder for a string whose value is inserted by the application program at run time.

3 Query Generation

From the database point of view, an API module is a collection of simple view definitions whose extensions are represented by terms conforming the type definitions. These views are encoded as a logic program defining a predicate `hasType(T,V)`. It formally defines the set of values `V` having type `T`, i.e., the semantics of the type `T`. The database system is modelled by two predicates for accessing information:

- `In(X,C)` denotes that the database object `X` is an instance of the concept `C`, e.g., `In(e2341,Employee)`, `In("Peter Wolfe",String)`.
- `A(C,a,X,Y)` states that the object `X` is related to the object `Y` by an attribute `a` which is defined in class `C`, e.g., `A(Employee,name,e2341,"Peter Wolfe")`.

The logic program can automatically be generated from the type definitions by a simple top down traversing algorithm on the syntax tree of a type definition[1]:

For each concept `C` imported in the API module we include a clause which delivers all values of type `C`.

```
hasType(C,C(_X)) :-
   In(_X,C).
```

A tuple type has the general form `T/C = [a1:T1,...,ak:Tk]`. The decoration `C` is called the "class" of T. It is mapped to the clause pattern

```
hasType(T,T(_X,_Y1,...,_YK) :-
   In(_X,C),
   <map(a1:T1)>,
   ...
   <map(ak:Tk)>.
```

The parts `<map(ai:Ti)>` have to be mapped as follows:

- If `Ti` is a set type `{S}` where `S` is a type name for a tuple-valued type with arity `m` then `<map(ai:Ti)>` is replaced by

```
SET_OF(S(_Z,_Z1,...,_Zm),
    ( A(C,ai,_X,_Z),
      hasType(S,S(_Z,_Z1,...,_Zm))),
    _Yi)
```

- If `Ti` is a set type `{*S}` where `S` is a type name of a tuple type with class `D` then `<map(ai:Ti)>` is replaced by

```
SET_OF(REF(S,_Z),
       ( A(C,ai,_X,_Z),
         In(_Z,D)),
       _Yi)
```

- If `Ti` is a tuple type with arity `m` then the macro is replaced by

```
_Yi = Ti(_Y,_Z1,...,_Zm),
A(C,ai,_X,_Y),
hasType(Ti,_Yi)
```

- Finally, pointer types `*Ti` where `Ti` is a record type with class `D` are mapped to the condition

```
(_Yi = REF(Ti,_Y),
A(C,ai,_X,_Y),
In(_Y,D);
_Y = null_value)
```

The operator ';' stands for a logical disjunction. There will be no backtracking on this disjunction. Thus, `_Y` will either be bound to a term `REF(.,.)` or to the special value `null_value`.

The PORT clauses specify those subsets of types which are of interest to the application program. A port definition

```
PORT v: {T| a1.a2...an=$P}
```

is compile to the clause

```
askPort(_S,v,_P) :-
  SET_OF(_X,
     (hasType(T,_X),
      path(_X,[a1,a2,...,an],_P),
     _S).
```

The predefined predicate `path` evaluates the path expression `a1.a2...an` starting from `_X`. Note that the parameter `$P` becomes an argument of the `askPort` predicate. It is instantiated by the application program when calling the goal `askPort`. The result is returned in the first argument.

The restriction in the port definition can easily be extended to contain several conditions. Moreover, one can allow a constant or a second path expression instead of the parameter on the right-hand side of the equality.

[1]We adopt the syntax of Prolog to denote the clauses. Variables start with an underscore. The meta predicate `SET_OF(x,c,s)` evaluates `s` as the set of all elements `x` satisfying the condition `c`

```
hasType(String,String(_S)) :-
  In(_S,String).

hasType(Project,Project(_P)) :-
  In(_P,Project).

hasType(DeptType,DeptType(_D,_DN,_M)) :-
  In(_D,Department),
  _DN = String(_Z1),
  A(Department,_D,deptName,_Z1),
  hasType(String,_DN),
  _M = REF(EmpType,_Z2),
  A(Department,_D,head,_Z2),
  In(_Z2,Employee).

hasType(EmpType,EmpType(_E,_N,_PS,_DT)) :-
   In(_E,Employee),
   _N=String(_Z1),
   A(Employee,_E,name,_Z1),
   hasType(String,_N),
   SET_OF( Project(_Z2),
     (A(Employee,_E,project,_Z2),
      hasType(Project,Project(_Z2))),
      _PS),
   _DT = DeptType(_D,_DN,_M),
   A(Employee,_E,dept,_D),
   hasType(DeptType,_DT).

askPort(_S,e,_N) :-
   SET_OF(_X,
        (hasType(EmpType,_X),
        path(_X,[dept,deptName],_N),
        _S).
```

Figure 2: Logic program for the example

3.1 Mapping of the Example

The definition of hasType for the running example is presented in Figure 2.

The values of the imported concepts are represented as unary terms, e.g. String("Peter Wolfe"). Values of complex terms have more components according to the type definition. For example,

```
EmpType(e2341,String("Peter Wolfe"),
        [Project(p1),Project(p2)],
        DeptType(d41,String("Marketing"),
         REF(EmpType,e3331)))
```

is the term representing a value of EmpType. Values of set types like {Project} are sequences of values of the member type enclosed by brackets. The component for the dept attribute is avalue of type DeptType. This shows the representation of pointers as terms REF(T,X) where X is the identifier of the value (of type T pointed to. The identifier is always the first component of a term T(X,...). All identifiers are constants from the database.

4 Properties of Interfaces

Termination of the logic program is guaranteed, and the types defined in API modules can be compared with the database schema and with each other.

4.1 Termination

On first sight, the generated logic program is recursive in the hasType clause and it contains complex terms as arguments. Thus, one has to ensure termination when evaluation it by the SLD strategy for logic programs.

Fortunately, if one makes sure that the types in the API module are defined non-recursively, then there is a partial order on the type names. If a type definition for T1 uses a type T2 on the right-hand side, then $T1 > T2$ holds. The definition of the logic program generator propagates this property to all clauses of the hasType predicate: if hasType(T,.) occurs in the condition of a clause hasType(R,.) then T must be smaller than R. Consequently, the logic program terminates on each goal hasType(T,X)[2].

A corrolar of this proposition is the finiteness of the sets interpreting the types in the API module.

4.2 Reasoning Services

The constructs in the API module were deliberately choses to be conformant with the concept language dialect of Buchheit *et al.* 1994. A couple of reasoning services are possible, each determing a different set of axioms to be reasoned about. We illustrate only one service, type checking against the database.

The type definitions in an API module make assumptions about the structure of the imported database concepts. In the example of Figure 1, the concepts Employee must at least have three attribute categories name, project, and dept. For the Department concept, two attributes categories deptName and head are required. Moreover, attribute cardinalities for the answer objects are stated:

- a set-valued attribute like project does not induce any cardinality constraint;
- a pointer-valued attribute like head restricts the the number of attribute fillers to be less or equal 1;
- the remaining attributes like dept must have exactly one filler.

Please note that these properties apply to the defined concepts like EmpType (*ET*) and not to the imported concepts like Employee (*E*). The concept language expression is:

$$ET = E \sqcap (= 1\ name.S) \sqcap (= 1\ dept.DT)$$
$$DT = D \sqcap (= 1\ deptName.S) \sqcap (\leq 1\ head.E)$$

As prescribed by the logic program, the pointer-valued attribute head of DeptType is not refering to EmpType directly but to its associated class Employee. Thereby, circular concept definitions are prevented.

These equalities for the type definitions are true provided the database schema has a schema consistent to it. At least it has to fulfill the following "well-typedness" axioms[3]:

[2] One has to assume that the underlying database is finite. This is however a standard assumption with databases.

[3] The symbol $\top$ stands for the most general concept.

$$E \sqsubseteq \forall name.\top \sqcap \forall project.\top \sqcap \forall dept.\top$$
$$D \sqsubseteq \forall deptName.\top \sqcap \forall head.\top$$

One can check this by adding it to the database schema and checking its consistency. The service would just make sure that all referenced attributes are defined in the database schema.

With a stricter regime, one can demand that the database schema must have the same or sharper cardinality constraints and that the well-typedness is refined to the concepts appearing as attribute types in the API module:

$$E \sqsubseteq ET \sqcap \forall name.S \sqcap \forall project.P \sqcap \forall dept.DT$$
$$D \sqsubseteq DT \sqcap \forall deptName.S \sqcap \forall head.ET$$

Here, the database schema has to fulfill the structure of the types in the API module. Consequently, all instances of the database concepts will apply to the type definitions. The type definitions would only

regards this as a too narrow coupling, the test on consistency of the above axioms with the database

are generated from the API module by a compiler. Since the **askPort** predicate can only return syntactically correct terms, an exception handling for malformed answers is superfluous.

6 Related Work

Lee and Wiederhold 1994 present a mapping from relational database schemas to complex objects. It is more general in the sense that arbitrary arities of the relations are allowed. In this paper, we assume a totally normalized schema of the database consisting of unary relations for class membership and binary relations for attributes. The advantage of our approach is that the algorithm for the generation of the logic programm can be kept free of reasoning on foreign key dependencies.

Plateau *et al.* 1992 present the view system of O_2 as complex type definitions coupled with the database types and with prescriptions for graphical display. The type system contained in the O_2 data

compiler.

The Interface Description Language IDL by

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Terminological logics for schema design and query processing in OODBs*

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1 Introduction

The paper introduces ideas which make feasible and effective the application of Terminological Logic (TL) techniques for schema design and query optimization in Object Oriented Databases (OODBs).

Applying taxonomic reasoning and TL in database environment for traditional semantic data models led to a number of promising results for database schema design and other relevant topics, as query processing and data recognition. In particular, in [Bergamaschi and Sartori,1992] a general theoretical framework has been presented, which supports conceptual schema acquisition and organization by preserving *coherence* and *minimality* w.r.t. inheritance, exploiting the framework of terminological reasoning. Complex object data models, recently proposed in the area of OODBs, are more expressive than actually implemented TL languages in some aspects. For instance, most of the complex object data models introduce a distinction between objects with identity and values, which is not present in TL languages. Further, complex object models usually support additional type constructors, such as set and sequence. Most importantly, these models usually support the representation and management of cyclic classes. These problems have found a solution in [Bergamaschi and

Nebel,1992; 1993], by the adoption of an extended TL, named ODL.

A real database specification always includes a set of rules, the so-called *integrity constraints*, which should guarantee data consistency. Constraints are expressed in various fashions, depending on the data model: e.g. subsets of first order logic, or inclusion dependencies and predicates on row values, or methods in OO environments. In particular OO methods are programs whose semantics cannot be inspected by an automatic reasoner. A first, necessary, improvement is to express at least a class of integrity constraints at schema level. Our proposal is to generalize the notion of a database schema including a declarative specification of a set of integrity constraints and to exploit this knowledge together with taxonomic reasoning for the different tasks of schema design and query optimzation. Let us examine separately the two aspects of schema design and query optimization.

2 Reasoning services in schema design

Provided that an adequate formalism to express integrity constraints is available, the following question arises: Is there any way to populate a database which satisfies the constraints supplied by a designer? Means of answering to this question should be embedded in automatic design tools, whose use is recommendable or often required in the difficult task of designing non–trivial database schemas.

Our proposal is to use the tableaux-calculus technique to guarantee schema consistency, therefore including state constraint consistency. Such a solution is actually a modification of existing algorithms for Description Logics [Schmidt-Schauss and Smolka,1991; Hollunder and Nutt,1990; Hollunder *et al.*,1990; Donini *et al.*,1991].

In order to substantially enhance OODBs with reasoning features, the next step should be the design of a front–end to the DB to validate insertions and updates, with respect to the extended schema description.

2.1 Examples

Let us consider the organizational structure of a company in order to explain the purpose of our constraint validation method. Assume the following: Employees have name and salary. Managers are employees and have a level composed of a qualification and a parameter. Repositories have a denomination, wich can be either a string or a structure composed by a repository name and an address; a repository stocks a set of at least one and at most five materials. Materials are described by a name and a risk. Departments have a denomination (string), and are managed by a manager. Warehouses have all the properties of departments and repositories.

The above description is expressed in our formalism, ODL extended, as follows:

$$\sigma(\texttt{Level}) = [\texttt{qualification}: \texttt{String}, \texttt{parameter}: \texttt{Int}]$$

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$$
\begin{aligned}
\sigma(\texttt{Employee}) &= \triangle[\texttt{name}: \texttt{String}, \texttt{salary}: \texttt{Int}] \\
\sigma(\texttt{Manager}) &= \texttt{Employee} \sqcap \triangle[\texttt{level}: \texttt{Level}] \\
\sigma(\texttt{Repository}) &= \triangle[\ \texttt{denomination}: \texttt{String} \sqcup \\
&\qquad\qquad [\texttt{rname}: \texttt{String}, \\
&\qquad\qquad\ \ \texttt{address}: \texttt{String}], \\
&\qquad \texttt{stock}: \{\texttt{Material}\}_{(1,5)}] \\
\sigma(\texttt{Department}) &= \triangle[\texttt{denomination}: \texttt{String}, \\
&\quad\ \texttt{managed-by}: \texttt{Manager}] \\
\sigma(\texttt{Warehouse}) &= \texttt{Department} \sqcap \texttt{Repository}
\end{aligned}
$$

(TKRS)). Informally, *semantic equivalence* means that the transformed query has the same answer as the original query on all databases satisfying the IC rules. The notion of semantic query optimization for relational databases was introduced in the early 80's by King [King,1981a; 1981b]; Hammer and Zdonik [Hammer and Zdonik,1980] independently developed very similar optimization methods. During the last decade, many efforts have been made to improve this technique and to generalize it to deductive databases [Shenoy and Ozsoyoporate any possible restriction which is not present in the original type but is *logically implied* by the type and by the schema. EXP(S) is based on the iteration of this simple transformation: if a type implies the antecedent of an IC rule then the consequent of that rule can be added. Logical implications between these types (the type to be expanded and the antecedent of a rule) are evaluated by means of the *subsumption computation* [Brachman and Schmolze,1985; Bergamaschi and Sartori,1992; Bergamaschi and Nebel,1993].[1]

At run time, we add to the compiled schema the query Q and activate the process again for Q, obtaining EXP(Q), with possible new *isa* relationships is obtained. If new *isa* relationships are found, it is possible *to move the query down* in the schema hierarchy. The main points of our optimization strategy are:

1. The *most specialized query* among the equivalent queries EXP(Q) is computed. During the transformation, we compute also, and substitute in the query at each step, the *most specialized classes* satisfying the query.
2. A filtering activity (*constraint removal*) is performed by detecting the *eliminable* factors of a query, that is, the factors logically implied by the query.

3.1 Examples

Let us extend the schema of the previous section with the class dangerous-shipment, which has the same structure of shipment. The following integrity constraint can be specified on it: for all shipments it must hold that if the risk of the material is greater than 3 then its urgency must be greater than 10 and it must belong to the class dangerous-shipment. The constraint can be embedded in the class description, obtaining the following type description for **Shipment**:

$$\begin{aligned}\sigma(\texttt{Shipment}) &= \triangle[\texttt{urgency:Int}, \texttt{item:Material}] \\ &\sqcap(\neg(\triangle\texttt{item}.\ \triangle\,\texttt{risk} > 3)) \sqcup \\ &(\texttt{DShipment} \sqcap \triangle\texttt{urgency} > 10))\end{aligned}$$

Let us give two simple query optimization examples related to our schema.

Q: "Select all shipments involving a material with risk greater than 8"

$$Q = \texttt{Shipment} \sqcap (\triangle\texttt{item}.\ \triangle\,\texttt{risk} > 8)$$

From the rule on Shipment, we derive:

$$\begin{aligned}\text{EXP}(Q) &= \texttt{DShipment} \sqcap \\ &(\triangle\texttt{item}.\ \triangle\,\texttt{risk} > 8) \sqcap \\ &(\triangle\texttt{urgency} > 10)\end{aligned}$$

The query is optimized by obtaining the *most specialized generalization* of the classes involved in the query itself.

[1]The subsumption is similar to the *refinement* or *subtyping* adopted in OODBs [Cardelli,1984; Lecluse and Richard,1989].

Furthermore, the factor $(\triangle\texttt{urgency} > 10)$ can be added if some advantageous access structure is available for it.

Another rewriting rule proposed in [Shenoy and Ozsoyoglu,1989; Siegel *et al.*,1992] is the *constraint removal*, i.e., removal of implied factors. We formalize constraint removal by subsumption. As an example, consider the query:

Q: "Select all the shipments involving a material with risk greater than 8 and urgency grater than 5":

$$Q = \underbrace{\underbrace{\texttt{Shipment} \sqcap (\triangle\texttt{item}.\ \triangle\,\texttt{risk} > 8)}_{S} \sqcap (\triangle\texttt{urgency} > 5)}_{S'}$$

In the schema with rules S is subsumed by S', as $explo(S)$ is subsumed by S' in the schema without rules. Thus, S' can be eliminated from Q.

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Semantic Indexing Based on Description Logics

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Abstract

A method for constructing and maintaining a 'semantic index' using a system based on description logics is described. A persistent index

Basic entities:		
patient	:<	anything.
examination	:<	anything and not(patient).
observation	:<	anything and

examinations[1]. Patients are related to examinations via hasExam, and examinations to observations via hasItem.

```
examSomeBpSysAbnorm   :=
  examination and some(hasItem,
                       bloodPressureSystolic and
                       abnormal).

patSomeBpAbnorm       :=
  patient and some(hasExam, examSomeBpAbormal).
```

Table 2: Defined concepts

Table 2 gives two examples for named descriptions (defined concepts) using the primitives. examSomeBpSysAbnorm is an examination which has an item which is an abnormal systolic blood pressure, and patSomeBpAbnorm is a patient which has an examination which has an abnormal blood pressure. Defined concepts are syntactic sugar for abbreviating possibly complex descriptions.

```
bloodPressureSystolic and all(hasValue, gt(140))
      =>  abnormal.
bloodPressureSystolic and all(hasValue, 110..140)
      =>  normal.
bloodPressureSystolic and all(hasValue, lt(110))
      =>  abnormal.
```

Table 3: Rules

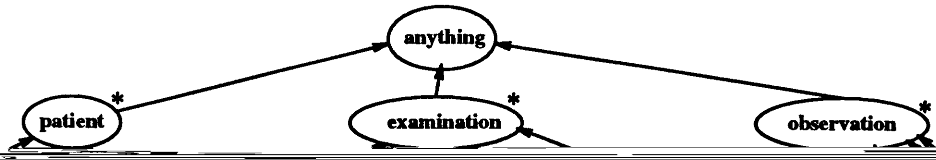
Descriptions are also used to define rules, which are expressed as implications between two descriptions. The

patient1	::	patient and hasExam:closed(*hce1* and *hce2*).
hce1	::	hce and hasItem:closed(*bpsys1* and *bpdia1*).
hce2	::	hce and hasItem:closed(*bpsys2* and *bpdia2*).
bpsys1	::	bloodPressureSystolic and hasValue:130.
bpdia1	::	bloodPressureDiastolic and hasValue:90.
bpsys2	::	bloodPressureSystolic and hasValue:150.
bpdia2	::	bloodPressureDiastolic and hasValue:95.

Table 4: Object descriptions

an asterisk) are related by subsumption links; disjointness has been left out for the sake of simplicity. The individuals at the bottom of the graph, a patient with two examinations, each of which with two observations, are linked to the most specific concepts they instantiate. For example, bpsys2 is classified under the conjunction of bPSystolic, which was explicitly told, and abnormal, due to an abnormality rule as in the example above. This leads to the classification of hce2 under examSomeBpSysAbnorm ('an examination with an abnormal systolic blood pressure') which in turn triggers the classification of patient1 as an instance of patSomeBpSysAbnorm ('a patient with an examination containing an abnormal systolic blood pressure'). Note that hce2 (patient1) was explicitly told to be only an examination (patient); the more specific concepts were derived by the system as a consequence of the role filler relations, the definitions and the rules.

In the following, two properties of description logic based systems not present in mainstream database sys-


anything
patient
examination
observation
*
*
*

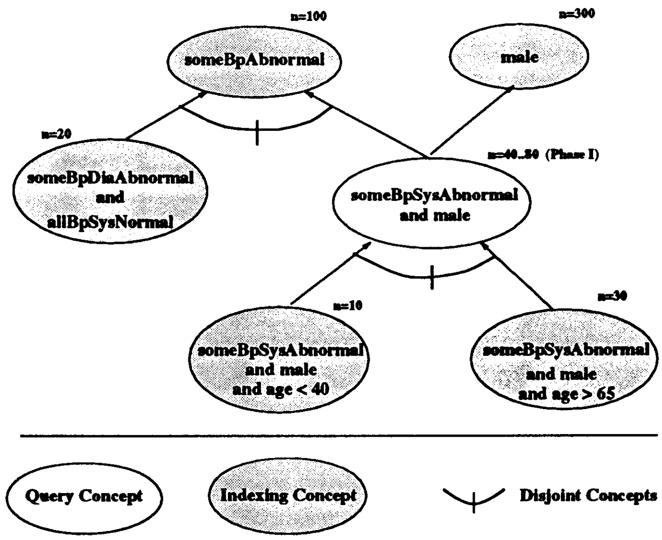


Figure 2: Approximating the cardinality of a query

ing indexing concepts. If we ask for a concept which is equivalent to an indexing one, we get the exact cardinality. If we ask for a concept which is totally unrelated to existing indexing concepts, i.e. there are no subsuming, no subsumed, and no disjoint ones, we will get a lower bound of 0 and an upper bound equal to the number of indexed instances. This means no information at all from the index. Typically, one should get something in between, some partial information.

The second phase additionally utilizes the actual extensions of indexing concepts also stored in the index. This generally results in much better cardinality estimates at the cost of having to load the instances, computing intersections and unions, etc. In case the query is a combination of indexing concepts, its exact extension (and cardinality) can be computed.

Otherwise there is a remaining set of candidates, the individuals for which the query is not known to be either true or false. In this case the index alone does not contain enough information to determine the extension of the query, and the third phase must be entered. For each candidate instance the original description must be accessed and explicitly tested against the query. After this has been done, the user can choose to declare the query as a new indexing concept, making the index more dense at that particular point in the semantic space.

4 Concluding Remarks

This semantic indexing mechanism is crucially dependent on reasoning with descriptions as provided by terminological systems. The indexing elements are potentially complex descriptions logically related by subsumption and disjointness. Note that incomplete algorithms for computing subsumption are not disastrous for indexing: they will simply result in a less informed, suboptimal index.

Compared with standard value-based indexes, this results in the following characteristics:

(1) A semantic index is inherently multidimensional since any combination of properties cast into a DL concept (i.e. an arbitrary query) can serve as an indexing element.

(2) As a structured concept the indexing elements are not just attribute values, but can be based on complex descriptions of related individuals.

(3) A semantic index as a whole is highly adaptable to patterns of usage. Indexing concepts can be added or removed at will, making it very dense and precise w.r.t to interesting sets of individuals, or very sparse in other, less interesting areas.

(4) Since the index is actually a set of partial descriptions for the indexed instances, lots of information (such as cardinality estimates) can be drawn from the index alone without accessing (possibly remote) individual descriptions at all.

These properties may turn out useful for building local information servers which cache information at various levels of completeness, depending on usage patterns.

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The Problems of Data Modeling in Software Practice

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Abstract

This paper presents, from the author's perspective, the problems that occur in practice during data modelling. The author's experiences are a result of a considerable number of projects which he carried out in the framework of his consultancy role at USU Softwarehaus in Möglingen (Germany).

These projects concerned the following themes:

- Corporate Datamodelling
- Comparing Datamodels
- Project (Application)- related Data modelling.

In all cases, E/R-notation was the chosen representation-form. From these experiences, the author formed an impression of the problems that occur in practice when defining a data model. These problems have, however, also led to the author's increased interest in knowledge representation, in turn leading to his usage of KR-methods in practice. This has shown itself to be quite effective.

Sections 2 and 3 briefly illustrate the recommendations and the experiences arising from their usage in projects.

1 Datamodelling in Practice - the Problems

Datamodelling was still up until recently the buzzword with which one believed to be able to solve the software crisis. CASE products concentrated on this area, meta-databases were created using a data-modelling process (E/R), and large companies invested millions in order to acquire a corporate data model. Although this trend has subsided a little, the theme in general is still of current interest. What Chen already recognised as an important benefit when presenting the E/R-Model, is today still seen as a key effect of a data model: the representation provides a standard communications basis with which understanding between DP and users is more easily accomplished.

This however, unfortunately seems to hold just for small data models. For larger areas of attention, the methodology starts to become ineffective, and no longer provides the overview required. Apparently, there are just a few 'gurus' who are able to create a complete complex data model. Often this data model quickly decreases in value, as soon as that person leaves the company. Director's offices exist in which the corporate data model is hanging up behind glass - however, this is regrettably the only place in which the data model is noticed or paid heed to.

The following problems, among others, have been recognised:

1.1 Low Expressivness of a Data Model in E/R-Form

During the analysis phase, many of the organisation's interdependencies and processes are identified. These are subsequently, to use the relativly inadequate language of the E/R-Model, abstracted and generalised. This often requires a change in terminology; in other words a unified, formal language is compulsory. What many authors (e.g. Vetter) see as an advantage of data modelling (exactly this coming-into-being of a corporate, unified terminology) often turns out to be a disadvantage: the terms used in the data model are not understood by the user departments. To make matters worse, these terms are mostly held in commentary form (if at all). Also the cross-reference of the new, unified terminology to the terms used in the departments is, in most cases, not documented at all. This makes understanding the data Model afterwards very difficult (see 1.6).

1.2 The Development of the Data Model is not Documented

A model undergoes many changes during the modelling phase. Requirements, ideas and practical examples from the user department contribute to the permanent extension and improvement of the model. Consequently, variations in the Business Processes are represented by generalisations, and classes (e.g. Subtypes) are created in order to denote similar 'things' in the model. The problem is that in nearly every case the documentation of this development is missing, i.e. reasons and reflections on which the model's structures and elements are founded will be lost after a short time. This results in difficulties if the model is changed due to further development or new requirements.

1.3 The Ideal Model is Developed

Although the user departments are consulted during the analysis phase, in practice one is often left with the impression that the DP-staff's ideal model is developed. This trend is strengthened by the fact that the creation of the data model requires a change in terminology and a certain generalisation (see 1.1). The user department staff usually see themselves therefore as incapable of effectively contradicting the 'high-flying' ideas of their DP-colleagues. The result is mostly a model which gives the impression of absolute perfection, but which neither makes the day-to-day business its priority, nor is so understandable that the user-departments can work with it.

1.4 Weak Methodology of the Developer

The possibilities of graphical development tools and the resulting excellent representation often disguises the weakness in the developer's understanding of the methodology. In this way, entities such as 'Total Turnover' and 'Turnover per Customer' can actually be modelled. Most developers tend to model concepts as entities, instead of taking the expressive character of entities in general into account. (This behaviour is also to be seen in a completely different form, where the developers come from a very technical background and mean tables or files instead of entities. Let's leave this point for the moment - it will be touched upon again in point 1.8). Another weakness is the missing experience in interview technique. Very often, the interviewer's question is formulated like "And how can I show that in E/R?" instead of "Which process stati occur in practice - let's leave E/R out of it for the moment?".

1.5 Exceptional Cases Become the Core of Model

Since the daily business of a company is in most cases comparatively simple to represent, Data Modelling projects often rush headlong into attempting to build every case imaginable into the model, as if the knowledge for treating each of these cases really had to be documented. The effect of this is that the models quickly become too detailed and difficult to understand - so much so that the user-departments, who really should judge the model's 'correctness' - more or less make this judgement on the basis of 'gut-feeling'. If they see well-known terms and recognise relationships between them that are held to be [illegible]

discusses entities and relationships, whose meanings are comparatively trivial and thereby are a matter of interpretation and alteration when trying to understand the 'fact-content' behind them.

1.7 Missionary character of DP

DP tends to over-estimate itself in many organisations. This inaccurate estimation doesn't particularly affect the importance of DP for the organisation's success so much (This could certainly be the subject of heated discussion both in theory and in an organisation's leadership). This obviously false judgement of one's own situation affects the implementation of standards and norms much more. The standardisation of terminology (mentioned under point 1.1) which the DP-Department carries out during data modelling is here an excellent example. It implies however, that 0.5 - 2 % of the company can dictate the terminology of the remaining employees. This over-estimation, together with the problem outlined in 1.3, means that DP doesn't model according to requirements, rather use their own ideas as basis for the 'ideal model'.

1.8 Too much Technical Thinking

Since most modellers come from a technical background (e.g. Application Development), they find it extremely difficult to ignore this technical knowledge when modelling. In the past, many cases occured where performance considerations were incorporated into the E/R-Diagram. The problem, however, goes much deeper than that. Most modellers cannot imagine any way to represent the characteristics of entities other than with attributes. Two entities with the same attributes are hastily made one, without considering that they express a classification on a logical level.

2 Suggestion for a Solution

The approach this solution takes is basically to use to best effect the developer's (and the user department's) tendency to express himself in concepts. This means that in the initial Data modelling phase, one creates a model of these concepts in the form of a semantic network. It's quite possible that other, more modern, representations are more suitable for this task. However, since the author has his roots in the Data modelling world, moving towards semantic networks was the easier way for him to come to terms with knowledge representation methodology.

This means that there is no unification of language necessary. Rather, the individual terms are cross-referenced to one another.

- **Generation of an E/R-model.** The user department requirements can be generated using all of the semantic networks. The E/R-Model can be worked on using this basis and can be tested using the requirements represented in the networks. This model is then the basis for the creation of the relational model.

To make the consolidation of several semantic networks developed by several developers possible, a standardized, unified representation of the networks is suggested. This means that only two types of associations are allowed, represented by lines; all other relevant concepts and associations appear as nodes. This restriction forces the unified representation necessary for the consolidation. The following two types of associations are allowed to be represented by lines:

- Type 1, which describes just the extension of a concept
- Type 2, which defines the intention.

Note that these associations are not defined by their symbolic meaning, rather by a relatively formal context. This has the advantage that the semantics of these associations are not interpretation-dependent.

3 Experiences from Projects

The suggested methodology solves the aformentioned problems. The interviewers interview-technique is positively affected, because his anno-

OLSEN: An Object-Oriented Formalism for Information and Decision System Design

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1.□Introduction

The Object oriented model has spread widely within programming languages during the last years. The principles of this model have had a great influence on analysis and design techniques. However no existing method is able to manage the whole analysis-specification-design-implementation cycle, preserving the homogeneity of the model used in different stages and the coherence by passing from one stage to the following.

We think that the global management of the life cycle cannot be solved, with the existing state of knowledge, by one unique miraculous method, which could adapt to every kind of application. We think on the contrary that the problem should be treated by a panel of methods dedicated to a particular domain.

For this reason we have developed the OLYMPIOS model at the LLP-CESALP laboratory. This model covers the life cycle of every application in the field of Information and Decision Systems for Manufacturing Firms. OLYMPIOS uses algebraic techniques, transformation rules and a predefined entity organisation to propose an original approach for object oriented design of information and decision system.

2.□OLYMPIOS Model Concepts.

The information processed in an enterprise, which we call industrial information, is a complex datum. An information and decision system (IDS) must take this complexity into account. We propose to represent industrial information through four main facets :

- data, describing the different entities handled by the IDS and the actions that they can perform or can be subjected to ;
- temporal properties of the different kinds of processes (including traceability of information) ;
- organisation, considered through information flows;
- economic facet, which describes the means of performance evaluation in relation to enterprise environment and objectives.

The OLYMPIOS model [Beauchêne□93] [BHP□93] [BHS□93] covers the different stages of such a system life cycle and proposes original solutions for its analysis, specification, design and realisation. OLYMPIOS describes activities, taking into account the assigned objectives and the resources availability. The basic modelling elements are□:

- an industrial information database, where products, resources, machines,... are described.
- Consumer-Supplier Information Systems (**CSIS**). A CSIS stands for an "atom" of organisation. It is a generalisation of the customer-supplier exchange relationship to every couple of actors in the enterprise (men, machines, software). Every CSIS is associated to an objective, transforms resources and emits a satisfaction level.
- an Objective Management System (**OMS**), whose role is to create a graph from expressed objectives, where every node is an objective associated to a CSIS.
- a Resource Management System (**RMS**), in charge of the product and resource management and sharing.
- an activation system (**AS**), producing actions plans to organise processes, taking into account the application, temporal constraints, and communications/synchronisation between CSIS.

3.□The IDS Life Cycle

The OLYMPIOS model covers the different stages of the IDS life-cycle (Fig.□1). We use an algebraic approach for the four facets of industrial information so as to obtain a coherent (i.e. sufficiently complete and consistent) specification. The design stage enables us to design the information system from specification and by analysing the "existing" system of the enterprise and its objectives. The result of this stage is a representation of the IDS using structured entities. The OLYMPIOS model introduces the uniformity of the model used from specification up to design. It uses tools proving the coherence of the system in the specification step and maintaining this coherence by automating the translation from one stage to another.

3.1.□Analysis Stage

In the analysis stage, the relevant information for the data, the temporal, the organisational and the economic facets is collected.

The result of the **data** facet analysis consists in the description of the data handled (resources etc.) in the system to design and, for each datum, the set of operations that can be realised (data dictionary). This static description can be translated into a finite state automaton in which every node represents a state of the datum in question and every edge an operation which produces a new state.

The analysis of the **organisational** aspects of the manufacturing firm results in a set of interactions between the different agents of the enterprise in the form of exchange relationships. By interviewing each of these agents we enumerate, on the one hand, the exchange relationships in which he is consumer, i.e. follows a certain objective by asking for satisfaction of the respective needs, and on the other hand, we identify the relationships in which he is supplier and performs a certain function. For each of these functions (which we would like to call basic operation) he enumerates the resources necessary for realising this operation and the algorithm he follows to obtain the wanted resource.
Thus, this interview gives us information about

- objectives and their decomposition,
- identification of the possible suppliers for the realisation of a given objective,
- the basic operations that can be performed and knowledge about how to execute the operations and which resources are needed.

stage. This automatic construction is realised by the algorithms [Nkongo 90] developed in our laboratory.

3.2.2. Organization Specification

It starts from the analysis of the "existing system", which results (inter alia) in the identification of actors and their functions and objectives. Specifying organisation consists in formally expressing identified objectives (in the "triple" form), and in constructing their associated CSIS from standard parametrized ASAT of organisation [Beauchêne 93]. Simultaneously, one must elaborate the different graphs of objectives.

3.2.3. Temporal Specification

The specification of the industrial information temporal facet uses a synchronous process algebra, directly derived from the SCCS calculus of R. Milner [Piard 93]. We specify four kinds of processes with this language :

1 - chronological and event-based clocks, essential to

3.2.4. Economic Specification

This facet cannot be specified independently of data and organisation. Indeed it is shared between them, and the most important part is included in the organisation facet. Works are still going on to sharpen the economic view of OLYMPIOS on the information system (with the help of performance indicators, fuzzy logic and project-based management approach).

3.3. Design Stage

The OLYMPIOS model, in its design stage, is based on the class model. This model was extended in order to allow to take all industrial information features into account, in particular real time ones. The result of the design stage is an organisation of entities independent of possible target programming languages : OLSEN (OLympios Structured ENtity).

An OLSEN [Guetari 94] is composed of a "class" part and another part called "scenario" which indicates the interactions with its environment. The difference between an OLSEN and a classical object is the scenario which describes the temporal behaviour generally missing in the standard class model. The OLSEN model is a "design object".

In this paper, we present only the specification and design of Activation System (AS part) and Resource Management System (RMS). The Objective Management System is the subject of a publication to come.

4. The Transition from the Analysis to the Specification Stage

This stage consists in describing data types using finite state automata. We must first insist on the fact that every entity cannot be described by an automaton. Only if it has successive states and if it is concerned by actions passing from one state to another can it be described by an automaton. We do not use the automata as a specification tool but as a tool allowing us to shape the evolution of some kind of data type over a set of states. In this kind of automata, each transition represents an operation changing the entity's state and each node represents one state of the entity. The automata may have many transitions corresponding to the same operation, however, each state is unique. A particular state called "starting state" must always exist. It corresponds to the extremity of the transition which stands for the operation creating the type of interest (TI).

The entities described by automata are distinguishable by the successive states that they can have. The order in which different states are occupied is well defined. The graph of state changing is oriented and has a starting state from which we can observe the evolution of the entity. This graph allows us to distinguish the constructor operations using a single method. The transitions corresponding to these operations have extremity nodes which can be reached from the starting state by only one path of the graph. The construction of axioms is done in two steps : the construction of left parts of axioms and the construction of right parts of

The construction of left parts of axioms :

The construction of axioms left parts consists of building the following sets :

- $CT = \{c(y^*), c \in C\}$
- $OT = \{o(x, y^*), o \in O, x \in CT\}$
- $ST = \{s(x, y^*), s \in S, x \in CT\}$

OT and ST contain the left parts of specification axioms. Axioms which define the semantic of the abstract data type have their left parts in the OT set and axioms which shows the simplification of terms of $T(\Omega,\Sigma)$ have their left parts in the ST set.

The construction of right parts of axioms :

The graph of states, whose every node is a state of entities of TI type, and whose every transition is an operation, provides :

1- $\Omega = \{TI, STATES\}$, $STATES = \{E1, E2, E3, ...\}$
2- $\Sigma = \{state, \sigma1, \sigma2, \sigma3, ..., \sigma n\} = O+C+S$, $T = S + C = \{\sigma1, \sigma2, \sigma3, ..., \sigma n\}$ is the set of operations which create or transform the values of TI (represented in the automata by transitions), O={state} contains a single observer.
3- Left parts of axioms by the building of AC,AO,AT from O,C et T.
4- Right parts (y) of axioms in the form *state(c(x*)) = y*, where $c \in C$, and y is the expression of the name of the node extremity of the path represented by c(x*) from the starting state. If there are many of these paths then the y term will be expressed in the form **if**...**then**...**else** ...
5- Right parts (y) of axioms in the form *s(c(x*)) = y*, where $s \in S$ is a convertible operation and y corresponds to the canonical form of the state extremity of the path c(x*), i.e. the expression of the shortest path between the starting state and the state extremity of the path represented by the expression c(x*). In other terms, these axioms are represented in the automata by simple circular paths. If there are many of these paths then the y term will be expressed in the form **if**...**then**...**else** ...
6- Preconditions related to the state of arguments (membership of TI) of each operation, which are expressed by the restrictions on the domain of this operation before its execution. These restrictions are issued from the state origin of the arc representing the operation.

5. The Transition from the Specification to the Design Stage

The transition from the specification stage (ASAT and SCCS) to the design stage is done automatically in two steps. The first step consists in taking the ASAT one by one and translating each one into a standard class. The second step is a global one and permits the organization of the communication between the obtained classes. The benefit of this automation is the preservation of the coherence obtained in the specification stage.

5.1. The Standard Class Generation

The class attributes and methods are generated from the ASAT operations. This is done using the following rules. We note an operation : $\sigma : \Omega_1 \rightarrow \Omega_2$, Ω_1 is the set of domains and Ω_2 is the set of codomains. "TI" is the data type that we specify. We distinguish three kinds of operations :

- Case 1 : $\sigma : \Omega_1 \rightarrow \Omega_2 / TI \notin \Omega_1$ and $\Omega_2 = \{TI\}$. This kind of operation corresponds to a particular constructor. For each constructor, we generate a method "*New*" with parameters of type Ω_1.
- Case 2 : $\sigma : \Omega_1 \rightarrow \Omega_2 / \Omega_1 = \{TI\}$ and $\Omega_2 = \{\omega \neq TI\}$. This kind of operation corresponds to observers. The class structure is obtained from these observers. For each observer we generate an attribute of type Ω_2 and a method to access it.
- Case 3 : $\sigma : \Omega_1 \rightarrow \Omega_2 / TI \in \Omega_1$ and $TI \in \Omega_2$. This case corresponds to a general one. For each operation of this kind we generate a method with in parameters of type $\omega \in \Omega_1 / \omega \neq TI$ and out of parameters of type $\omega \in \Omega_2 / \omega \neq TI$.

The scenario of an OLSEN is issued from SCCS formulae. An SCCS formula contains several deterministic parts. Each part provides one script in the OLSEN scenario. The scenario generation is done in three steps : the first two provide the declarative part of a scenario, the third one provides the dynamic part. For each OLSEN, we determine the determinist parts of the corresponding BEHAVIOUR (separated by a "sum" operator). For each part, we execute the following three steps□:

- **Event Detection**. This step permits the detection and declaration of the different kinds of events. The type of each event is deduced from the SCCS syntax. A communicational event appears in at least two BEHAVIOURs, once preceded by the delay operator δ, and once without this operator. An environmental event is identified by the existence of a clock emitting this event. An event is conditional if its complementary event appears at least once in a BEHAVIOUR. When all events are declared, we proceed to the unification of the communicational events. This unification is based on the *observational equivalence* [Austry□84] and consists of giving the same name to two synchronously successive events in a SCCS formula.
- **Identification of the Set of Suppliers**. For each communicational event, we define its receiving OLSENs whose BEHAVIOURs contain this event, preceded by the delay operator δ. Any OLSEN responding to this event by applying one of its methods must be added to the suppliers list of the treated OLSEN.
- **Script Generation**. A script is generated for each determinist part. Each event described in the formula is replaced by one or several simultaneous dispatches of messages. The receivers of these messages are the suppliers defined in step 2.

6.□The Transition from the Design to the Realization Stage

This transition is based on the realization programs which we have obtained in the analysis stage.

The OLSEN formalism helps us to generate data bases on the realization stage. The application programs are obtained through the OLSEN, the realization programs and the CSIS organization.
If we target object-oriented data bases in the realization stage, we have to use the OLSEN and the realization programs. In this case, each class part of an OLSEN is directly translated into a data base object and the scenario part is used for the data access in the application programs. The realization programs allow us to implement the methods of the data base objects.
If the data bases are not object-oriented, only the structure of the OLSEN interferes for the realization of these data bases. In a relational data base, for example, the OLSEN structure is used for the table creation. The inheritance relationship is eliminated in these data bases and replaced by the result of merging the structures of a super-class and the sub-classes.

In the realization stage we can obtain three different types of CSIS translations: automatic CSIS where the actors perform totally automated processes, semi-automatic CSIS where one of the two actors performs an automated task or the manual CSIS where both actors perform manual tasks.

The first type of CSIS with the realization programs and the scenarii allow us to obtain the application programs. These programs will act upon the data bases with the classical operations like add, modify and delete. These interactions with the data base are performed through message sending between the data base objects in the case of an object-oriented data base or through primitives which are the result of the OLSEN behaviour in the case of non object-oriented data bases.
The semi-automatic CSIS form the interactions between a user and a process. These CSIS lead towards the implementation of user interfaces and external views which restrict the data base access according to the user's rights.
The manual CSIS finally, allow us to realize the manual procedure for which the automation would be too expensive.

7.□Conclusion

The OLYMPIOS model provides the means to analyse and specify coherently an industrial information and decision system. It allows then to design the specified IDS by preserving the coherence obtained in the specification stage by using algebraic techniques. The continuity and uniformity claimed by the Olympios model is the result of two factors□:

- the use of algebraic tools to specify all the components of an IDS like the data facet, the organization facet or the temporal facet,
- the use of ASAT to specify data and Objects to design them.

This care of continuity and uniformity has lead us to develop algorithms (and parts of a future CASE-Tool) to automatically generate a coherent OLSEN organisation from the analysis. Our objective is to generate a maximum of code for applications.

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Frames, Objects and Relations: Three Semantic Levels for Knowledge Base Systems*

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Abstract

We propose an architecture for large-scale

elaborated here). Section 2 introduces the three level architecture and discusses its merits. The mappings from FRM to COCOON and from COCOON to a relational database management systems in terms of efficient processing of set-oriented retrieval and update operations and supported transaction mechanisms. For this reason, we choose to map our object data model to a relational storage system. This mapping is specifically tailored to support the retrieval and update patterns initiated by the frame model. As a result, we have a three level architecture as indicated in Figure 1.

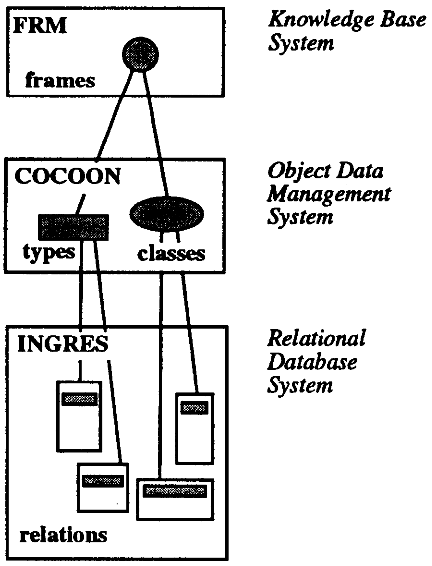

Figure 1: Three Level Architecture

The knowledge model FRM is mapped to the object data model COCOON which in turn is mapped to a relational system. At present, we use the relational data base management system INGRES, but the mapping can easily be altered for other relational systems.

3 From Frames to Objects

A discussion of the differences between the knowledge representation and semantic data modelling approaches is given in [Bor 91]. One of the main differences often quoted is that database models tend to be prescriptive rather than descriptive. Thus the underlying assumption is that the database provides a complete, current and consistent description of the application domain; any attempt to input data which is not consistent with the database model will be rejected. Knowledge models tend to be descriptive and it is quite acceptable that the model may have to be revised according to new information received into the system. This is most clearly visible in a knowledge-based system with some learning capabilities (see e.g. [Mor 91]).

A further general distinction between data models and knowledge representation languages is the fact that data models have a much clearer separation between intensional and extensional information. Intensional information is given by a database schema which is relatively stable and thus plays a predominant role in determining efficient storage, retrieval and update strategies for operations on extensional data.

Ideally, for the support of knowledge base systems, we wish to have the latter property of database models (i.e. efficiency) but not necessarily the former (i.e. being prescriptive). In this respect the COCOON object data model is a good candidate for the support of the frame model FRM.

In this paper we consider only a subset of FRM which corresponds to the common frame constructs: slots, slot entries, and cardinality restrictions. For example,

Skilled-Person $\doteq$
  (and *Person*
    (all *has-skills Skill*)
    (exist *has-skills Rare-Skill*)
    (atleast *has-skills* 3))

defines a frame class *Skilled-Person* as a subclass of *Person* with the slot *has-skills* that represents the relationship *has-skills* to the class *Skill*. The slot requires at least 3 values at an associated class instance; one of those entries must be an instance of the class *Rare-Skill*.

COCOON has a strong influence from both semantic data models and knowledge representation languages (especially KL-ONE [BS 85]) in terms of semantic expressiveness. It supports not only complex object structures but also rich classification structures and high-level operations over collections of objects. As a result, the semantic expressiveness of COCOON is at a similar level to that of FRM with the main difference between the two models stemming from the fact that FRM supports more specialised inference mechanisms. In some sense COCOON may be considered as lying somewhere between the prescriptive and descriptive paradigms. A COCOON class represents a semantic grouping of objects and may have an associated predicate condition. For example

define class *Youngsters* : *person* **some** *Persons*
  where *age* $<$ 30;

defines a class *Youngsters* which contains objects of type *person* and is a subclass of *Persons*; further there is an associated predicate condition that specifies that its members should be less than 30 years old. The object type *person* declares what functions are applicable to an object of that type and may look like the following

define type *person* = *age* : **integer**,
  name : **string**, *has-skills* : **set-of** *skills*;

A formal mapping from frame structures to object structures and from query operations on frame knowledge bases to object bases has been defined and implemented. While concept class descriptions in FRM are based on a single representation structure – the frame, COCOON has two basic representation structures – the type and the class. Types describe what properties and relationships to other objects an object can have whereas, as stated above, classes deal with semantic groupings of objects. Only a small number of the frame constructs for concept class descriptions can be mapped to COCOON

FRM concept class description:

Comp_Delivery $\doteq$ (**and** (**all** *supplier Company*)
(**exist** *supplier Computer_Company*)
(**all** *recipient Company Person*)
(**atmost** *recipient* 1)
(**all** *ispart Workstation*)
(**all** *price* [0, 100])
(**atmost** *price* 1))

Corresponding COCOON type definition:

define type *comp_delivery* = *supplier* : **set-of object**,
recipient : **object**,
ispart : **set-of object**,
price : **integer**;

Corresponding COCOON class definition:

define class *Comp_Delivery* : *comp_delivery*
where $supplier \subseteq Company$ **and**
$\emptyset \neq (supplier \cap Computer\_Company)$ **and**
$recipient \subseteq (Company \cup Person)$ **and**
$ispart \subseteq Workstation$ **and**
$\emptyset =$ **select** $[(i < 0)$ **or** $(i > 100)]\,(i : price)$;

Figure 2: Example of Mapping an FRM Concept Class Description to COCOON Types and Classes

type definitions but all of them to COCOON class definitions. As a consequence, frames of FRM are mapped to some combination of types and classes in COCOON. To increase the possibilities for compile-time optimisation, we designed the mapping such that as much information as possible is provided on the type level.

Figure 2 shows an example of mapping an FRM concept class description to COCOON types and classes. In a first step the object type *comp_delivery* is derived from the FRM class *Comp_Delivery* such that for every **all** construct (i.e. for every slot) we have a function with the same name. In case of a slot with a maximal cardinality of 1 the function is single-valued, otherwise set-valued. In a second step the COCOON class *Comp_Delivery* of type *comp_delivery* is generated from the frame class *Comp_Delivery*. With the type reference we ensure that the class will contain only objects with the right functions being applicable. With the associated class predicate we cover the remaining features of the FRM concept class description. As a result, the COCOON class defines the same necessary and sufficient conditions on class membership as the frame class does. Note that the three object-valued functions in the type definition *comp_delivery* are all of type **object**. This is because providing more specialised function ranges (e.g. *supplier* : **set-of** *Company*) would not lead to a simpler class predicate. As this would not reduce the amount of dynamic type checking necessary we decided to keep the mapping to the type level simple and to map always to object-valued functions of type **object**. For details see [LNR+94].

The establishment of the mapping from frames to

In knowledge base systems a query for objects with certain properties is usually established as a class description. The result of the query is all the objects subsumed by that class so that in this case query evaluation amounts to inferencing. To support such queries on our COCOON-based FRM we have specified a second mapping that transforms a frame class description to be interpreted as a query into an equivalent expression of the COCOON object algebra (cf. example in Figure 3). This algebra expression is then evaluated on the COCOON object base derived from the original frame knowledge base. At that point query optimisation techniques, which are highly developed in the database area, can be employed. We hope that this will lead us to a query processing that is much more efficient than evaluating a query frame by the inference mechanism of FRM.

4 From Objects to Relations

In mapping an object data model onto a relational system, there are many choices to make concerning both the representation of objects and also of classes. For example, all the properties of an object may be stored together in a single relation or split over several relations. In the former case, there are problems of how to represent multi-valued properties. In the latter case, several join operations may be required to reconstruct an object.

With the representation of classes, the choices arise because an object may belong to many classes and the prime decision is whether to store an object only with its most specific class – or to store it in all classes – or to have some form of compromise be

Query Frame:

(**and** (**all** *supplier Company*)
    (**all** *recipient Company*)
    (**exist** *recipient Insurance_Company*)
    (**all** *product*
        (**and** *Workstation*
            (**all** *has-cpu Sparc*) (**atleast** *has-cpu* 2))))

Corresponding Algebra Expression:

$$\mathbf{select}[supplier(o_1) \subseteq Company](o_1 : Objects) \cap$$
$$\mathbf{select}[recipient(o_1) \subseteq Company](o_1 : Objects) \cap$$
$$\mathbf{select}[recipient(o_1) \cap Insurance\_Company \neq \emptyset](o_1 : Objects) \cap$$
$$\mathbf{select}[product(o_1) \subseteq \mathbf{select}[has\text{-}cpu(o_2) \subseteq Sparc] \cap \mathbf{select}[\#(has\text{-}cpu(o_2)) \geq 2](o_2 : Workstation)](o_1 : Objects)$$

Figure 3: Example of Mapping a Query Frame to an Object Algebra Expression (still to be Optimised)*

the class explicitly as it can be derived at access time. The trade-off here is between fast access to explicitly stored classes versus high update overheads if data is replicated unnecessarily.

In our mapping of COCOON onto a relational storage system, we employ extensive replication to minimise retrieval costs. For example, all classes are represented explicitly even those which could be specified in terms of a query expression (view) over other classes. Since an object may belong to many classes, an object representation may be replicated in several relations. The penalty associated with such an approach of massive replication is the cost of update operations; a single update operation on a specific object may require updates on a large number of relations involved in the representation of that object.

The problem then becomes one of how to speed up the time for updates. This is achieved by implementing the update operation as a number of simpler update operations which can be executed in parallel. The exploitation of intra-transaction parallelism together with multi-level transactions is a key technique towards such improved performance [WS 92].

We are currently evaluating the above approach to

and relations. The introduction of the object level is beneficial in reducing the semantic gap between the frame level and the relational level and enabling the utilisation of structural semantic information for query and update processing. The mapping from the object level to the relational level allows the use of well-established, efficient mechanisms for data storage, data access, data sharing and recovery under failure.

At present, we have implemented mappings for structural information from the frame model, FRM, to the object model, COCOON and from COCOON to the multiprocessor relational database system, INGRES. We also have a mapping from frame query classes to COCOON algebra. Moreover, there are some early results on the parallelisation of update operations over a COCOON database represented in INGRES [Rys 94]. Currently, we are working on the mapping of the remaining operational components and on the mapping of frame class instances to objects.

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Uniformly Querying Knowledge Bases and Data Bases

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Abstract

Present KL-ONE-like knowledge base management systems (KBMS), whilst offering highly structured description languages aside efficient concepts classification, have limited capability to manage large amounts of individuals. Data base management systems (DBMS) can, instead, manage large amounts of data efficiently, but give scarce formalism to organize them in a structured way, and to reason with them.

This paper shows how assertional knowl- [illegible] uniformly accessed. A technique to tightly couple KBMS with DBMS [Borgida and Brachman,1993] is described. As in [Devanbu,1993; Borgida and Brachman,1993] we let primitive concepts and relations in a KB correspond respectively to unary and binary tables/views in a DB. Unlike [Devanbu,1993; Borgida and Brachman,1993] we provide a *tight coupling* between KBMS and DBMS, i.e., a *on demand* access to the DB, instead of a *loose coupling*, that requires a pre-loading of the data from the DB into the KB. In this way we obtain the following advantages:

- more complex queries than simply asking for the instances of concepts can be done; just as an ex-

description $\mathcal{W}^3$; we say also that the set of data expressed in a DBox constitutes a *data base* $\mathcal{D}$. Assuming that two complete query answering functions separately exist, for both the ABox and the DBox, a *knowledge base* $\mathcal{KB} = \langle \mathcal{T}, \mathcal{W}, \mathcal{D} \rangle$ can be defined in such a way that a uniform query function, based on the two answering functions, can be implemented. We do not require any special capability from the DBox, except the one of (quickly) retrieving lists

mixed (KBMS/DBMS) queries can be answered in a coherent way, but, to this extent, we need to *couple* the terminology $\mathcal{T}$ in $\mathcal{KB}$ with the data base $\mathcal{D}$. This coupling consists in the association of some particular terms of $\mathcal{T}$ with tables, in the DB representing $\mathcal{D}$, where the extension of these terms are to be found.

For sake of simplicity we adopt, next, some restrictions on the form of $\mathcal{KB}$, even if, as it will be noted later, they can be, at least in part, released.

4.1 Translating Queries into SQL

When each predicate in a query $q = \lambda\overline{x}.P_1 \wedge \ldots \wedge P_n$ can be made correspond to a set of tables in the DB, where the answers have to be found, it can be translated into an equivalent SQL query. Of course, the sets of tables can be easily found via the marking function M. At this point we have just to cope with the union set of tables $\{T_1, \ldots, T_h\}$ and their bindings via the variables in $\overline{x}$. For simplicity, let us suppose that the tables returned by M are composed by one column in the case of a concept (let it be called `left`), and two in the case of a relation (let them be called `left` and `right`). The SQL translation is of the kind:

```
SELECT DISTINCT  select-body
FROM             from-body
WHERE            where-body
```

where the *select-body* is a list of column names of the kind $M(P_{x_i})$.`left` or $M(P_{x_i})$.`right`, one for each variable x_i in $\overline{x}$, according to the fact that the variable x_i appears for the first time in the predicate P_{x_i} in the first place[7] or in the second place, respectively. The *from-body* is the list of all the tables involved – i.e., all the $M(P_i)$. The *where-body* is a list of SQL `where`-conditions of the kind `field2=field1` or `field2=constant`, where the first form has to be used for each variable that is used more than once, each time it is reused, and the second form occurs for each use of constants. In both the forms `field2` is a selector similar to those in *select-body*, corresponding to positions in the query where the variable is further used or where the constant appears, respectively; `field1` corresponds to the first occurence of the variable.

4.2 The General Case

In general answering, a query is more complex and requires the merging of results from the DBMS and the KBMS. *Answering* a query in $\mathcal{KB}$ means finding a set $\{\overline{x}^1, \ldots, \overline{x}^m\}$ of tuples of instances s.t., for each tuple $\overline{x}^i$, $\lambda\overline{x}.(P_1 \wedge \ldots \wedge P_n)[\overline{x}^i]$ holds in $\mathcal{KB}$. We call such tuples *answers* of the query and the set of all of them its *answer set*.

Due to the definition of answer of a query, it is obvious that, in order to avoid the generation of huge answer sets, free variables should not be used, i.e., each variable appearing in $\overline{x}$ must appear also in the query body (i.e., the part at the right of the dot). Indeed, we adopt a stronger restriction, be-

relevant result of answering an unconnected query is equivalent to the union of the single results of separately answering the clusters, in the sense that all the information is included in it. But, if we consider the formal definition of answer, we must consider the fact that the overall result must contain tuples longer than those resulting by submitting the single clusters; to obtain all the tuples satisfying the definition of answer the single answers have to be combined by a sort of *Cartesian product*. More exactly, if, after having reordered the variables, un unconected query is written as $\lambda\overline{x}.\varphi_1(\overline{x}_1) \wedge \ldots \wedge \varphi_n(\overline{x}_n)$ – where $\overline{x}$ is the concatenation of the other vectors ($\overline{x} = \overline{x}_1 \cdot \cdots \cdot \overline{x}_n$), and $\varphi_1(\overline{x}_1), \ldots, \varphi_n(\overline{x}_n)$ corresponds to the single clusters – and given that the asnwers sets of a generic cluster $\lambda\overline{x}_i.\varphi_i(\overline{x}_i)$ is $S_i = \{\overline{I}_i^1, \ldots, \overline{I}_i^{j_i}\}$, the answer set of the whole query is $S = \{\overline{I}_1^{j_1} \cdot \cdots \cdot \overline{I}_n^{j_n} \mid \overline{I}_1^{j_1} \in S_1, \ldots, \overline{I}_n^{j_n} \in S_n\}$.

The case of a *connected* (i.e., non unconnected) query $\lambda\overline{x}.\varphi(\overline{y})$ with unbound variables can be reduced to the case of an unconnected query $\lambda\overline{x}.\varphi(\overline{y}) \wedge T(\overline{z})$, where $\overline{z} = \langle z_1, \ldots, z_k \rangle$ contains all the variables appearing in $\overline{x}$ but not in $\overline{y}$, and $T(\overline{z}) = top(z_1) \wedge \ldots \wedge top(z_k)$, where *top* correspond to the most generic concept in $\mathcal{T}$.

It is now clear that unconnected queries and queries with unbound variables may have unreasonably large answer sets, without giving any further capability to the system. Therefore, we consider only connected queries with only bound variables.

To afford the answering of a query we need to split it into sub-queries that can be answered by the two specialized query answering functions of the KBMS and the DBMS. To this extent we need, as a first step, to *mark* all the possible atomic predicates, corresponding to the terms in $\mathcal{T}$, and say that a term P is:

- DB-marked iff for each $t \in subs(P) \cap \mathcal{PT}$ $PM(t)$ is defined .
- KB-marked iff for each $t \in subs(P) \cap \mathcal{PT}$, $PM(t)$ is undefined.
- Mixed-marked otherwise.

These three markings reflect the fact that the instances (pairs) of P are all in $\mathcal{W}$, all in $\mathcal{D}$, or part in $\mathcal{W}$ and part in $\mathcal{D}$, respectively. The strategy for answering to a query is based on this information. Let us, first, observe that it is easy to answer to an atomic query where the predicate is a KB-marked or a DB-marked term. In the first case it is enough to where the P_i^{KB} corresponds to the KB-marked terms, the P_i^{DB} to the DB-marked terms, and the P_i^M to the Mixed-marked terms. The query can be split in the sub-queries: $q^{KB} = \lambda\overline{x}.P_1^{KB}\wedge\ldots\wedge P_{l_{KB}}^{KB}$, $q^{DB} = \lambda\overline{x}.P_1^{DB}\wedge\ldots\wedge P_{l_{DB}}^{DB}$, and $q^M = \lambda\overline{x}.P_1^M\wedge\ldots\wedge P_{l_M}^M$.

4.3 The Algorithms

As we said, the sub-queries q^{KB}, q^{DB}, q^M can be easily processed. The only difficulty is that some of the variables in $\overline{x}$ could be unbound in a sub-query. In this case, as shown before, the answer sets have to be completed, that is, the unbound variables should be made correspond to each instance in $\mathcal{KB}$, for all the found answers, by all the possible combinations. But, in this way, huge answer sets are generated, as in the following sketch of the query-answering algorithm:

1 split the query as sketched above into q^{KB}, q^{DB} and q^M.

2 submit q^{KB} to KBMS, q^{DB} to SQL (after translation) and transform each of the atomic subqueries q_i^M of q^M into a set of atomic queries corresponding to the leaf terms in $\mathcal{T}$ that specialize q_i^M; submit them to the specific retrievers.

3 collect all the answers respectively in the answer sets $AS_{\overline{x}_{KB}}^{KB}$, $AS_{\overline{x}_{DB}}^{DB}$, and $AS_{\overline{x}_M}^M$, and *complete* them with the whole domain in the place of unbound variables, as mentioned above, generating $AS_{\overline{x}}^{KB}$, $AS_{\overline{x}}^{DB}$, and $AS_{\overline{x}}^M$.

4 the overall answer set is just $AS_{\overline{x}}^{KB} \cap AS_{\overline{x}}^{DB} \cap AS_{\overline{x}}^M$.

Of course this first algorithm is widely space wasting. Moreover, in step 3 it is not clearly stated how to collect the answers of the sub-queries q_i^M. We try here to shortly describe this operation and to show how the completions of $AS_{\overline{x}_{KB}}^{KB}$, $AS_{\overline{x}_{DB}}^{DB}$, and $AS_{\overline{x}_M}^M$ in step 3, and their following intersection in step 4, can be obtained more efficiently. To solve these problems, from step 3 ahead a compact representation for $AS_{\overline{x}}^{KB}$, $AS_{\overline{x}}^{DB}$, and $AS_{\overline{x}}^M$ is needed. Let a generic partial answer set be written as $AS_{\overline{y}}$, where the variables of the original complete variable tuple $\overline{x}$ missing in $\overline{y}$ are, $x_{p_1},\ldots,x_{p_k}$. Its completion can be represented in a compact way with $AS_{\overline{x}} = \bigcup_{\overline{I}\in AS_{\overline{y}}}\{\overline{I}^{\star}\}$, where $\overline{I}^{\star}$ are equivalent to $\overline{I}$ except that are lengthened by filling the k missing positions $p_1,\ldots,p_k$ with any marker, e.g., a star '$\star$'. The star stands for all the individuals in $\mathcal{KB}$. Using this representation for the completion in step 3, it is now easy to rephrase step 4 of the algorithm as a merging operation. In fact answer sets $AS_{\overline{x}}^{KB}$, $AS_{\overline{x}}^{DB}$, and $AS_{\overline{x}}^M$ can be *merged* into a single answer set as follow:

4.1 let **result-list**=$\{AS_{\overline{x}}^{KB}, AS_{\overline{x}}^{DB}, AS_{\overline{x}}^M\}$

4.2 choose two answer sets, AS_1 and AS_2, in **result-list**, where answers have at least one common position filled by individuals, i.e., not $\star$.[8]

4.3 merge AS_1 and AS_2 by collecting only those answers in AS_1 where each non-$\star$ filled position is filled by the same individual or by $\star$ in some answers in AS_2, and replace in the collected answers each $\star$ with the individuals in the corresponding position in all the matching answers of AS_2

4.4 replace AS_1 and AS_2 in **result-list** with their merging computed in step 4.3

4.5 REPEAT from step 4.2 UNTIL only one item is left in **result-list**.

4.6 RETURN the only item left in **result-list**.

Now it is easy to explain how to collect the answers of the sub-queries q_i^M of step 2. It is enough, for each $q_i^M \in \{q_1^M \ldots q_h^M\}$, to collect all the answers of all its *descendant queries*, and complete these answer sets generating $AS_{\overline{x},1}^M,\ldots,AS_{\overline{x},h}^M$, as described above; it is now clear that, in the above algorithm for step 4, step 4.1 has to be so rephrased:

4.1-bis

let

result-list=$\{AS_{\overline{x}}^{KB}, AS_{\overline{x}}^{DB}, AS_{\overline{x},1}^M,\ldots,AS_{\overline{x},h}^M\}$.

The resulting algorithm, composed by steps 1, 2, 3 (modified as shown), 4.1-bis, and 4.2 to 4.6 has been implemented. In our system the KBMS currently in use is LOOM [MacGregor,1991], and the database query language is SQL, but, as mentioned, also other systems could be easily used.

5 Conclusion and Future Developments

We have shown how a third component, a DBox – allowing for the extensional data to be distributed among the ABox and the DBox – can be added to the traditional TBox/ABox architecture of KBMS. By means of the DBox is possible to couple the KBMS with, for example, a DBMS, and use both the systems to uniformly answering queries to knowledge bases realized by this extended paradigm. The presented query language has some restrictions, and some constraints have been imposed to the form of the knowledge bases. To overcome these limitations, some extensions of the present work can be proposed.

5.1 Constraints on the Form of $\mathcal{KB}$

In section 3 we assumed that some constraints should be imposed on the form of $\mathcal{KB}$. Indeed they can be in part released, even if this more general approach would require a deeper discussion and a reformulation of the algorithms. Here we try to give a very short account on possible developments in this direction. First, consider the **homogeneous extension** condition. It is important because it allows to make the search of the answers simpler, giving the basis for a neat separation between KB-marked, DB-marked, and Mixed-marked predicates[9]. But it

[8] Such two sets do always exist, otherwise the query would be unconnected, while we assumed to deal only with connected queries.

[9] and giving also the way to decompose the Mixed-marked predicates in sets of KB-marked and DB-marked ones.

is even more important when considered in conjunction with the **db isolation** condition. In fact we can easily cope with leaf terms having instances from both $\mathcal{W}$ and $\mathcal{D}$ by submitting the corresponding subqueries to both the specialized retrieving functions, and then proceeding with the merging as usual. But, allowing this ambiguity would make more complex the formulation of the **db isolation** condition, that could become:

- **db isolation**: all the leaf terms of $\mathcal{T}$ whose instances are even only in part in $\mathcal{D}$ are primitive and are not used in any other term definition in $\mathcal{T}$.

Indeed we can, at least in part, give up also with this condition. In fact, while keeping the fact that such term must be primitive – this is pragmatically coherent with the fact that the raw information coming from the DB cannot be inferred – we can allow such term to be used inside new, eventually even non primitive, definition. To this extent we need a much more complex schema for translating queries on DB-marked term into SQL. For example, if the query is of the kind $\lambda\langle x\rangle.C(x)$ where $C \doteq$ **some**(R, D), its SQL translation could be:

```
SELECT  M(R).left
FROM    M(R)
WHERE   M(R).right IN M(D)
```

Similarly, a translation for the **all** operator could be given, as in [Borgida and Brachman,1993], but in this case some extra considerations about the adequacy of the standard extensional semantics of this [illegible]

[illegible]

arise. In fact, the empty satisfiability of an **all** clause would be hardly suited for a DB.[10]

In the example above D is supposed to be a primitive atomic DB-marked concept. Another extension to be explored is about releasing this constraint. Again, some concerns about semantics adequacy should probably be adressed.

Also the **non intermediate db extension** condition has, after the considerations above, to be revised. In fact, even if we must still consider the informaton of $\mathcal{D}$, as they are given, as being *a priori* fully realized in the leaves of the taxonomy, because the tables in the DB, where the instances of $\mathcal{D}$ are described, are not structured in a hierarchy, it could

5.3 Aknowledgments

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