

# International Workshop on Terminological Logics

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# International Workshop on Terminological Logics

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The *International Workshop on Terminological Logics* was the follow-up event to the “Workshop on Term Subsumption Languages” held in Jackson Village, New Hampshire, in October 1989 (cf. AI Magazine 11(2)).

Terminological Logics consists of a family of representation formalisms that grew out of the KL-ONE knowledge representation system. Unlike some other areas of knowledge representation, in this field the aspects of theoretical work (semantical foundations, complexity), system-oriented work (implementational issues), and application-oriented work are all dealt with within one community, as documented by the variety of talks at this workshop.

The workshop itself brought together 40 invited participants currently working in the field, and served to provide a snapshot of the current state of research, showing that there has been a lot of progress in the last several years. The theoretical area has advanced to a point where only a few questions concerning the core formalism remain open. The current trend seems to be to integrate more functionality and other formalisms.

In addition to the scheduled sessions, there were a number of informal meetings for exchanging ideas and planning future collaborative work, including one about future system standards and standard notation. This should make the exchange of ideas, systems, and knowledge bases, and the maintainance of a test corpus easier in the future.

The program was rounded off by an overview talk by Ron Brachman on the past and future development of Terminological Logics (the issue of finding a good name for the field is still in discussion), and a panel debate on aspects of the relationship between “Theory and Practice”. In order to promote communication between people working in the field a mailing list (tlc@isi.edu) was established.

We would like to thank the Dagstuhl foundation for inviting us, our affiliated organizations for their support, Kirstin Ost for compiling this report, and finally all participants for their active engagement in the workshop.

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# Experiences in ‘Hybridification’

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As someone working in Natural Language Processing, Term Subsumption Languages (TSL) are something both very useful and not – yet – exactly what we would want to have. In my talk I gave an example of how results from linguistics (namely the Generalized Quantifier Theory, GQT) could be integrated into this paradigm of TSL, although at first glance there seem to be some conflicts.

In GQT, the structure of a quantifier (and the use of one determiner) induces sets of legalized inferences that can be used to derive new valid facts from a given GQT-term. The information transported when using a specific determiner for an assertion *has* to be taken into account, because in some cases, the standard TSL-inferences do not correspond to what GQT forces us to do.

## An Analysis of Taxonomic Reasoning

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We define taxonomic reasoning in a very broad sense as methods for automated deduction which exploit a partial order relation, like the inheritance relations used to build conceptual taxonomies. We examine whether such methods exhibit a performance advantage with respect to more traditional deductive techniques. A survey of a few systems supporting taxonomic reasoning is done, including Omega, LOGIN and Theory Resolution. We claim that the effective performance benefits come from interleaving taxonomic steps, which filter out alternatives, with deductive steps. We report data gathered from experiments on a first-order theorem prover, built on purpose, with and without the taxonomic reasoner. The preliminary results seem to substantiate the claim.

# Cyclic and Transitive Extensions of Concept Languages

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I have considered different types of semantics for terminological cycles in the concept language  $\mathcal{FL}_0$  which allows only conjunction and value restriction. It turned out that greatest fixed point semantics (gfp-semantics) seems to be most appropriate for cycles in this language.

It can be shown that the concept defining facilities of  $\mathcal{FL}_0$  with cycles and gfp-semantics can also be obtained in a different way. One may replace cycles by role definitions involving union, composition and transitive closure of roles. This proposes a way of retaining, in an extended language, the pleasant features of gfp-semantics for  $\mathcal{FL}_0$  with cyclic definitions without running into the troubles caused by cycles in this larger language: starting with the language  $\mathcal{ALC}$  - allowing negation, conjunction, disjunction, value- and exists-restrictions - we disallow cycles, but instead add the possibility of role definitions involving union, composition and transitive closure.

The main result is an algorithm which completely handles subsumption for this extended language. Surprisingly, this algorithm can also be used to handle subsumption w.r.t. cyclic terminologies of  $\mathcal{ALC}$ , if descriptive semantics is used for these cycles.

# A Conceptual Clustering Approach to Subsumption and Taxonomy

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By themselves, the purely intensional descriptions used to build KL-ONE concepts are not adequate as a theory of meaning. A conceptual clustering approach is used to provide a more general theory of subsumption and taxonomy by giving a balanced treatment of deductive and inductive reasoning. In addition to the standard deductive operations of classification and realization, the importance of reasoning about instances (as in case-based reasoning) is emphasized. This is accomplished by including inductive operations such as automatically generating a class description which applies to a set of instances, determining the similarity between two instances, and modifying existing class descriptions to accommodate exceptions. The clustering algorithm is based on a number of psychological theories of category formation.

## Subsumption in Database Environments

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The application of subsumption to semantic database models developed in database environment is relevant for many topics as: conceptual schema design, query validation and optimization. We proved that, by extending semantic data models with derived concepts and embedding a relationship in concept descriptions, we can compute subsumption and guarantee schema consistency, correctness and minimality. We also showed that data semantics of well known data models as Entity-Relationship, TAXIS, GALILEO, FDM and IFO is expressible in a terminological language equivalent to  $\mathcal{PL}_1$  and therefore semantic data models are tractable.



# **What Hath KL-ONE Wrought?**

## **An Informal Discussion of the Past and Future of KL-ONE-like Systems**

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Many of the ideas behind current work on terminological logics (actually, “object-centered description logics”) have their roots in early work on KL-ONE, begun as long as 15 years ago. KL-ONE was originally designed as a broadly expressive, “general purpose knowledge representation system”, and was strongly motivated by a need to overcome semantic imprecision in early knowledge representation work. Since the early 1980’s the goals of KL-ONE and its descendants have evolved and now related work proceeds on several fairly distinct fronts. Along the way a number of interesting and important results have been produced, at numerous institutions.

I have two goals here: first, I will attempt to get a clearer view of where we stand with “KL-ONE-like” systems, highlighting some of the key developments of the last 15 years, including systems, applications, formal results, and connections to other areas of research. In support of this I will reconstruct some of the key events in the early history of this technology. Second, I want to address the future. With an impressive record of both systems and mathematical successes behind us, it is time to turn our attention to significant applications and to the nature of our connection to the rest of the knowledge representation community. Other important issues to consider include how to educate potential users, experimenting with more assertional components, structural descriptions, and principled incompleteness. I will outline some of my concerns along these dimensions, and invite discussion of the future of our research community.

# Intensional Semantics and Relationships between Epistemology and Ontology

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One of the major assumptions in designing knowledge representation formalisms in the KL-ONE family, was the so-called “intensional representation”. An intensional representation is required when two descriptions have to be compared, or when they are interpreted by qualitative processes; in other words, many processes can be activated by using the global structure of a concept, and by interpreting its properties and the relationships between these properties. It is evident that an adequate representation of a concept involves the specification of the relationships existing between its descriptive parts: this is the classic problem of “structural descriptions”.

Ontology plays an important role in structuring knowledge. In order to create a knowledge base, one must make some assumptions about what kinds of things there are in the world; in other words, any user needs a general grammar for representing knowledge, but he must also be guided by using constraints depending on the nature of the things being modelled. This limits the generative power of the grammar, but, in any case, its expressive power increases, since putting together an epistemological formalism and a set of ontological constraints makes it possible to account for more subtle conceptual facts.

In this perspective, an intensional semantics for a typical terminological language has been designed which is similar to that of data types in programming languages. Primitive concepts are denoted by a set of values. Defined concepts are denoted by their properties. A role is denoted by a function which, given a tuple, returns the values of the property which individuates the role. Structural descriptions are considered as an object-oriented programming tool. More precisely, a function or a procedure can use the roles of a describing concept in order to refer to the roles of a described concept.

The properties of a concept play a relevant role from an intensional viewpoint, in the same way as types of concepts are essential if we look at the universe as a map of complex descriptions interacting one with the other. Such facts can be specified by using notions such as, for instance, sortal concepts, or natural, nominal and artifact concepts as defined in the psychological paradigm experiments about the relationships between epistemology and ontology are now being carried out, in the aim of both investigating the ontological adequacy of certain SI-Nets data structures and integrating epistemological tools with ontological constraints.

A system has been created in which the representational tools based on intensional semantics interact with an ontological representation of a portion of universe: in this way, a user can create a knowledge base by using this representation as a guide, imposing constraints on the descriptions of items and their insertion into the network.

# Tractable Concept Languages

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We present two concept languages, called  $\mathcal{P}\mathcal{L}_1$  and  $\mathcal{P}\mathcal{L}_2$ , which are extensions of  $\mathcal{FL}^-$ . We prove that subsumption in these languages can be decided in polynomial time. Both languages include a construct for expressing inverse roles, which has not been considered up to now in tractable languages. In addition,  $\mathcal{P}\mathcal{L}_1$  includes number restrictions and negation of primitive concepts, while  $\mathcal{P}\mathcal{L}_2$  includes role conjunction and role chaining.

By exploiting recent complexity results, we show that none of the constructs usually considered in concept languages can be added to  $\mathcal{P}\mathcal{L}_1$  and  $\mathcal{P}\mathcal{L}_2$  without losing tractability. Therefore, on the assumption that languages are characterized by the set of constructs they provide, the two languages presented in this seminar provide a solution to the problem of singling out an optimal trade-off between expressive power and computational complexity.

## Extending Hybridity within the YAK Knowledge Representation System

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YAK is a hybrid KR system, and in its foundations is similar to CLASSIC and LOOM. The core of the system is a “traditional” TBox/ABox hybrid representation language (with some peculiarities), enhanced, possibly in a “principled” fashion, with other hybrid modules representing different kinds of knowledge and reasoning. The system, fully implemented in CommonLisp (and with an optional graphical user-interface machine-dependent), is the main knowledge representation module of the AlFresco natural language system, a multimodal dialogue prototype for the exploration of Italian art history.

Motivations and new ideas for the KR field often are originated within the natural language processing community. Prototypical knowledge for prediction in natural language understanding, belief representation for user modeling in a multi-agent dialogue, and the possibility of representing sets to handle conjunctions, plurals and natural quantifiers are three aspects that we have taken into consideration.

# Modelling Domain Knowledge for NLP

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One objective of the ASL-project (Architecture for Speech and Language) is providing the domain model knowledge necessary for a dialogue system. Besides building up a conceptual structuring of the domain a normal problem is the mapping of words onto concepts where a word can stand for several concepts.

The domain modelling will be supported by using lexical semantic relations. Another aim of the project is to generalize about the modelled domain to arrive (probably, hopefully) at some kind of basic ontology.

## A Probabilistic Extension for Term Subsumption Languages

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We propose a probabilistic extension for terminological logics (TL) that maintains the original performance of drawing inferences on a hierarchy of terminological definitions. It however enlarges the range of applicability to real world domains determined not only by definitional but also by uncertain knowledge. As basis for our extension we use the TL  $\mathcal{ALC}$ . On the basis of the language construct “probabilistic implication” statistical information on concept dependencies can be represented. For guaranteeing (terminological and statistical) consistency several requirements have to be met. These requirements allow to derive further implicitly existent probabilistic implications.

# On Conceptual Indexing in Terminological Systems

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In a scenario of applying terminological systems to knowledge base management a frequently occurring task is the retrieval of instances of some query description. This task can be supported by a method we call “conceptual indexing” which essentially maintains references from concepts to their instances. Introducing the possibility to explicitly mark concepts as being indexing allows for determining the system’s query processing behavior. This is illustrated by demonstrating different choices for the selection of indexing concepts in the BACK system.

Making the notion of indexing concepts explicit is an example for devising categories of concepts, and use them for tailoring terminological systems for different testbeds or different applications.

## Reification in Meta-SB-ONE: Bridging the Object/Relation Dichotomy

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KL-ONE-like knowledge representation languages are neutral with respect to which kinds of things in the domain to be modeled should be regarded as *objects* and hence be represented by concepts, and which should be regarded as binary *relations* and thus be represented by roles. The few guidelines and conventions in this respect are contradictory and frequently violated. Problems arise as soon as one wants to combine two or more knowledge bases whose ontology conflicts with respect to this object/relation dichotomy. In this talk the Meta-SB-ONE representation language will be presented, which has been equipped with language elements that allow the same knowledge to be represented both through concepts and through roles, and allow both representations to be related to each other. The syntax, interpretation, and application of this language in the integration of conceptual knowledge bases will be presented.

# **Explicit Trade-offs between Completeness and Performance in the LOOM System**

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An important use of the LOOM classifier is as the constraint filter in a heuristic search program. Analogously with other evaluation functions, the completeness of the inconsistency test must be balanced against the cost to perform the test. We have observed that by reducing the completeness of the LOOM classifier “in the right way”, we can accelerate the total search time without reducing the completeness of the search.

A second issue of investigation is the choice of semantics for backtrack proofs in LOOM. Currently, LOOM implements the weakest (but most computationally efficient) of three possible semantics. Users can trigger this backchaining mode either via the mechanism that marks concepts as backward chaining, or by choosing to employ specialized classes of instances that are always evaluated only using backchaining.

## **The CLASSIC Knowledge Representation System: Implementation, Applications, and Beyond**

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Implementation, analysis, and application work with CLASSIC have provided opportunities for evaluating the usefulness and implications of our selection of term constructors. We have discovered that all of our applications depend critically on one or more constructs not found in some systems based on terminological logics. We report on user needs (and demands) for sets, individual fillers in concept descriptions, coreference constraints, host language escapes, and simple rules.

We discuss some of the advantages and complications that these features introduced from the perspective of both system designers and knowledge engineers.

# The Complexity of Concept Languages

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Concept languages provide a means for expressing knowledge about hierarchies of concepts, i.e. classes of objects with common properties. The basic reasoning tasks to be performed on concepts are satisfiability checking and subsumption checking. We consider a family of languages, called  $\mathcal{AL}$ -languages, which covers most of the concept languages considered in the literature. Our work has two aspects. Firstly, we develop a general technique for checking satisfiability and subsumption of  $\mathcal{AL}$ -concepts, which is based on the tableau calculus for first order predicate logic. Secondly, we use this algorithmic technique to give precise upper and lower bounds for the  $\mathcal{AL}$ -languages, thus providing a complete analysis of the computational complexity of the satisfiability and the subsumption problem for concept languages.

## Representation and Use of Defaults in Terminological Systems

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It is often difficult to combine traditional theories of non-monotonic or default reasoning with KL-ONE-like systems because there is too great a mismatch in terms of the underlying models. I presented the underlying model for my theory of default reasoning in taxonomies and suggested that because of the representation using only strict links/implications in the terminology it may be possible to combine it successfully with a traditional terminological reasoning system.

In the default reasoning work the language has been much less expressive than that used in most terminological systems. Particularly properties of objects have been expressed as simple attribute value pairs rather than as roles containing other objects. More work needs to be done to ascertain whether this expressivity can be extended. Even without extended expressivity the combination of classificatory and default reasoning can be useful. We have a diagnosis system using both defaults and classification with a disease taxonomy. Disease symptoms are represented as features/attributes of disease concepts in an inheritance taxonomy.

# Handling Computational Difficulties with Reasoning in Terminological Logics

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I see two basic types of solutions to the problem of bad computational properties of reasoning in terminological logics. The first is to choose a better method of analyzing complexity and the second is to retreat to incomplete reasoning. I suggest that normal-case complexity analysis, along with analysis of reasoning algorithms, is the best way to study this complexity - not worst-case complexity. The problem with using incomplete reasoners is how to describe the inferences. Here I propose using abstract algorithms as ways of describing incomplete reasoners.

## Theory Unification: Use and Support

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We argue for a very practical way of integrating specialized reasoners like say CLP(R) or a terminological component into a logic programming environment: well defined hooks into built-in unification. This way the user of such a system can explicitly specify, how the system shall unify pairs of ‘meta-structures’ or how to unify a ‘meta-structure’ and a basic term. To implement such support for user-definable extensions to unification we propose to extend the WAM, an abstract machine capable of handling standard Prolog efficiently. The size of this modifications seems to be moderate: a few additional primitives and one additional case in most of all the unify\_X and get\_X instructions, plus an additional register to delay user-defined unifications. As an example we showed how unification could act as the ‘glue’ between different reasoners: one can express algebraic constraints on certain features of a feature term using e.g. CLP(R). Such generic feature terms could consequently be unified automatically yielding the correct combined algebraic constraint.

Furthermore we demonstrated, how the subsumption algorithm used in SB-ONE and in VIEKL handles cycles in the terminology. It is guaranteed to determinate for cycles. We conjecture, that the algorithm implements gfp-semantics; but right now we only have empirical results for this chain, no proof.



# Modeling and Reasoning

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When considering the integration of new constructs into the representation language, one should try to find out what can be modeled with them and what kind of inferences are licensed by them. Whereas from a theoretical point of view all inferences are determined by the formal semantics, from an applicational point of view it is useful to characterize the “interesting” inferences. These inferences are the ones that should be computed by incomplete algorithms and that should be computed efficiently by complete algorithms. For the implication link and role forming operators it turns out that the interesting inferences arise on the object level. As a consequence, concept classification should be viewed as just one inference component among others. Other inference components of terminological representation systems are the role classifier, the rule classifier and the recognizer. Though they are all based on concept classification they perform some important inferences on their own.

## A Correspondence Theory for Terminological Logics

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I have worked out several correspondences between Terminological Logics and propositional modal and dynamic logics. These correspondences turn out to be highly productive since they reveal that many terminological logics already have been investigated in the area of modal and dynamic logics. Since there is a lot of work on the complexity and model theory of modal and dynamic logics, we gain many new results for the corresponding terminological logics.

My starting point was a correspondence between the terminological logic  $\mathcal{ALC}$  and the propositional modal logic  $K_{(m)}$ . To see this correspondence, one has to realize that (a) atomic concepts can be interpreted as atomic propositional formulae and that (b) value restrictions can be interpreted as modal operators. That is, the value restriction  $\forall R.C$  can be expanded as “agent  $R$  knows proposition  $C$ ”.

Moreover, I have shown that a regular extension of  $\mathcal{ALC}$ , called  $\mathcal{TSL}$ , corresponds to the propositional dynamic logic. Using this correspondence, I proved that it suffices to consider finite  $\mathcal{TSL}$ -models, and that  $\mathcal{TSL}$ -subsumption is decidable. Finally, I have shown that the feature logic version of  $\mathcal{TSL}$  corresponds to the deterministic propositional dynamic logic.

# **A Temporal Terminological Logic**

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I reported about my attempt to integrate three well-known formalisms of knowledge representation: terminological logics in the tradition of KL-ONE, the temporal logic of Shoham, and Allen's interval calculus. Drawing on each of these sources, a temporal terminological logic is proposed which combines structural with temporal abstraction. A straightforward model-theoretic semantics is provided. In the talk, I motivated the basic constructs of this temporal extension by showing its utility in a monitoring scenario. In particular, it could be used to define relevant states, events and derived measures in terms of the primitive data being monitored, thus providing a "human window" to the mass data generated by a process.

## **STUF - Sorted Feature Terms and Relational Dependencies**

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We describe the key ideas of our unification-based grammar formalism STUF. It integrates feature terms with sorts and recursive definitions of relations. We argue that STUF gives us all the expressivity we need to encode grammars following the so-called principle-based approach, like HPSG. Yet, STUF has a very clear declarative semantics and also a simple operational semantics can be given. We outline our current implementation of STUF as an instance of a generalized constraint logic programming scheme.

# Terminological Reasoning over Feature Graphs

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Constraint systems based on feature graphs are employed in Logic Programming and Computational Linguistics. The fact that features are functional attributes and graphs are partially described in terms of their features yields a certain similarity with terminological languages. In fact, if sorts are added, general terminologies using only functional roles can be expressed. The restriction of roles to features yields more feasible computation. For subsumption and satisfiability of the corresponding concept descriptions it does not make a difference whether the terminology is interpreted with respect to all models or with respect to the subclass of models extending the fixed domain of feature graphs. In this framework, constraint simplification modulo the terminology amounts to forward inference similar to the assertional reasoning of CLASSIC. Moreover, constraint simplification modulo terminologies seems to be an interesting and natural extension to logic programming based on feature-oriented constraint systems.

## Using Terminological Logics in a Problem Solver

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In this talk, I discussed how we have been using LOOM, a terminological logic-based knowledge representation system in the context of the Explainable Expert Systems framework, a “shell” that makes expert systems easier to maintain and evolve and enhances their explanatory capabilities. Conventional expert system frameworks are seriously limited in providing these capabilities, due in part to problems in their underlying knowledge representation, specifically the use of low-level rules that implicitly encode and compile together different kinds of knowledge. This implicit, intertwined representation makes a system less modular and understandable and hence more difficult to modify or explain. In our approach to building expert systems, we provide a system builder with a framework that provides better support for abstraction, and that explicitly separates the different kinds of knowledge that go into an expert system. The EES framework then takes responsibility for linking together the different kinds of knowledge to perform problem solving. This approach uses the LOOM knowledge representation to provide the underlying knowledge representation capabilities and it uses the LOOM Classifier to link up the different kinds of knowledge through descriptive reference. We have found that this approach to expert system construction provides significantly improved explanation capabilities, and it appears to hold considerable promise for enhanced maintenance and evolvability.