Description Logics for Natural Language Processing

Enrico Franconi
Knowledge Representation and Reasoning Laboratory
IRST, I-38050 Povo TN, Italy
franconi@irst.it

Abstract

This paper surveys in short the activity of the Knowledge Representation and Reasoning group at IRST for Natural Language Processing. We have developed two Description Logic based systems to be used in large Natural Language dialogue architectures. The functional interaction of such KR systems with the other modules is briefly described. Then, several qualifying extensions of the basic systems are introduced, and their usefulness for natural language applications is explained.

1 Introduction

In the last seven years, the Knowledge Representation and Reasoning group has been working on the research and the development of a knowledge representation system based on Description Logics[1], which should meet the requirements of the various modules involved in a large natural language architecture.

The importance of description logics to represent the logical form of a sentence has been elsewhere emphasized (see e.g. [Lavelli *et al.*,1992]); description logics have been successfully applied in many working natural language dialogue systems, like XTRA [Allgayer *et al.*,1989], PENMAN [Bateman *et al.*,1990], JANUS [Weischedel,1989].

The main Natural Language project at IRST is the development of the ALFresco (*Automatic Language-Fresco*) interactive system, a multimodal dialogue prototype for the exploration of italian history, specifically fourteenth century painters and frescoes [Stock,1991; Stock *et al.*,1993]. A second project is the development of a natural language interface for the *concierge* of the IRST integrated system MAIA (*Advanced Model of Artificial Intelligence*), a mobile robot with intelligent capabilities in the domain of office activities (see [Bresciani,1992] for a description of how the domain is represented).

[1] I.e. a knowledge representation language of the KL-ONE family – also called Frame-Based Description Languages, Term Subsumption Languages, Terminological Logics, Taxonomic Logics or Concept Languages.

In our systems, the dialogue is based on typed utterances and on some limited form of hypermediality. The user can either ask direct or indirect questions, or request for actions. In future releases, assertions augmenting the domain knowledge of the system will be allowed. The user can use deictic references, by pointing to part of images displayed on the touch screen. The system replies with natural language sentences in the form of suitably selected hypertexts and active images.

The dialogue system architecture is roughly divided into six modules: the parser, the lexical discrimination module, the topic module, the quantification module, the interpretation module, the pragmatic module and the generation module. The KR system interacts with:

- the Lexical Discrimination module [Lavelli and Magnini,1991; Lavelli *et al.*,1992]: whenever the parser tries to build a constituent, the Discrimination module is triggered in order to check the *consistency* of the semantic part of such a constituent. In parallel, the module builds up a first logical form – where references and quantifiers scoping are still ambiguous – expressing the meaning of the sentence in the most specialized way with respect to the semantic lexicon and the background knowledge; this process is known as *concretion* [Jacobs,1992; Vilain,1993], and it is an abductive process. Heuristics is applied to the minimal form in order to obtain a preferential ordering of the semantically consistent interpretations. The background knowledge used at this level is represented in the so-called *Upper Model*.
- the Topic module [Samek and Strapparava,1990; Zancanaro *et al.*,1993]: builds up the semantically plausible referents for *linguistic expressions* such as definite NPs, pronouns and deictic references. It computes all the consistent referents, using also notions like semantic-proximity.
- the Interpretation module [Strapparava,1991]: the *validity* of the logical form over the background and domain knowledge is checked, and the referents for the quantified variables of the sentence are retrieved after the resolution of the quantifiers scoping. The expressivity of the logical form is obviously richer

than the one of the domain representation language; however, the interpretation of the logical forms relies on the lower language interpretation.

- the Pragmatic module: decides how to react in a given dialogic situation, considering the type of request, the context, the model of the interest of the user. It makes use of knowledge about the speech acts, the dialogue and the user model.
- the Generation module: a sentence is generated starting from the representation of its meaning. The generation of the rhetorical schemata is strongly correlated with the intensional knowledge represented in the terminology.

2 Description Logics Based Systems

The first KR system developed for the purposes briefly described in the preceding section was YAK [Franconi,1990; 1991b]. The core of the system is a "traditional" TBox/ABox description logic (with some peculiarities), enhanced, possibly in a "principled" fashion, with other hybrid modules representing different kind of knowledge and reasoning [Franconi,1991a]. The goal in the development of YAK was to enhance the expressivity of the language used for representing the background and the domain knowledge, to cover phenomena of natural language and provide powerful services for the interpretation of logical forms, from both a semantical and a computational point of view. We aimed to reduce the differences between the two representation languages. Moreover, another guideline of the project was the research and the development of a *formal* system, in the sense that it should be provided with formal syntax and semantics, and provably sound and complete reasoning algorithms. The system, fully implemented in CommonLisp (and with an optional graphical machine-dependent user-interface), is the main knowledge representation module of the AlFresco natural language system. YAK embodies the following characteristics:

- The terminological – TBox – language, derives from the very simple frame-based description language $\mathcal{FL}^-$; in addition, it allows for primitive concepts and roles, functional roles and role conjunction. A tractable and complete subsumption procedure is provided [Cattoni and Franconi,1990].
- An object-oriented ABox, with a complete recognition reasoning procedure. [Franconi *et al.*,1992; Nebel,1990].
- A Constraint Box which includes: disjointness, implies rules, transitive roles, test operator – to handle concrete domains.
- Constraints inference (à la Allen) added to the ABox, to exploit set reasoning – to handle conjunctions, plurals and natural quantifiers – together with temporal and spatial reasoning [Franconi,1992].
- A compositional unification-based query language with typed variables and simple logical connectives, necessary to build up queries during the interpretation phase.
- A simple mechanism for multiple KBs handling.
- "Viewpoints" according to the *relevant beliefs* theory for multiple agents beliefs representation [Franconi,1991a]; this is useful for user modeling in a multi-agent dialog.
- A Prototype Box where concepts expressed by prototypical properties are represented; the recognition reasoning mechanism takes into account the prototypical knowledge [Franconi *et al.*,1992].
- A *Concretion* reasoning service, checking the consistency of logical forms and computing the equivalent minimal form [Jacobs,1992].

Two years ago we decided to augment the expressivity of the terminological language, in the beginning because the representation of the meaning of more complicated natural language utterances called for disjunctions and negations. This lead us to start the CRACK project [Franconi and Tessaris,1994]. In this very ambitious project the propositionally closed language $\mathcal{ALC}$ [Baader and Hollunder,1991] is extended. The CRACK language differentiates itself from the other knowledge representation systems for its high expressivity and its provably sound and complete reasoning procedures. With respect to the comparable systems available in the research community, i.e. KRIS [Baader and Hollunder,1991; Baader *et al.*,1994], Classic [Brachman *et al.*,1991] and Loom [MacGregor,1988], CRACK is more expressive, it is expandable to new constructs, it treats the conceptual and individual levels in a homogeneous way, it is modular, it is comparably fast.

Special features handled currently by CRACK are: feature selection, agreement and disagreement; inverse roles; collections, parts and plural quantifiers; concrete domains; treatment of individuals in the terminological part; principled representation of time, events and plans; interface with relational databases via SQL queries [Bresciani,1994]. Moreover, the YAK hybrid modules representing constraints, beliefs and prototypes are still available within CRACK.

Another project we are carrying on is the development a completely new knowledge representation language, specifically for the representation of the relational knowledge involved in the lexical discrimination process. More about this in section 3 of this paper.

In the following, I will briefly present only some interesting extensions of description logics developed at IRST, which were intended specifically for natural language processing. Details of the single activities can be found in many papers cited within the paper.

3 A Relation-Based Description Logic

In this section, we will show the basic ideas for a formalization of KODIAK [Franconi and Rabito,1994], a knowledge representation language first informally introduced by Robert Wilensky in [Wilensky,1987]. This language

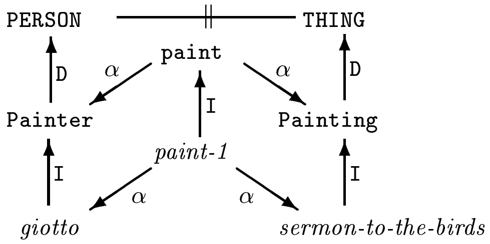

Figure 1: A sample KODIAK knowledge base.

is particularly suited for the representation of the lexical semantics knowledge during the disambiguation and concretion phases.

KODIAK is a relation-based description logic, as opposed to KL-ONE, which is a concept-based representation language. We consider here only a simplified version of the language. The syntactic types of the language are *Relations*, *Aspectuals*, *Absolutes*; the basic operators of the language are *Manifest*, *Dominate*, *Instantiate*, *Disjointness*. Figure 1 shows an example. The relation `paint` manifests the two aspectuals `Painter` and `Painting` which are dominated by the mutually disjoint absolutes `PERSON` and `THING`; *paint-1* is a relation instantiating `paint` and manifesting the instances *giotto* and *sermon-to-the-birds*. It is important to notice that this schema defines completely all the mentioned entities. The aspectual `Painter` *is defined* as being the first participant of the relation `paint`, whereas the relation `Paint` is defined as having two participants, namely `Painter` and `Painting`. On the other hand, the absolute `PERSON` is defined only as being disjoint from the absolute `THING`.

The knowledge base is so rewritten in the formal language:

DOMINATE (`PERSON`, `Painter`)
DOMINATE (`THING`, `Painting`)
DISJOINT (`PERSON`, `THING`)
MANIFEST (`paint`, `Painter`, `Painting`)
`paint` (*paint*-1, *giotto*, *sermon-to-the-birds*)
`Painter` (*giotto*)
`Painting` (*sermon-to-the-birds*)

In this language relations can be the arguments of other relations; for example, the following is a knowledge base expressing "Enrico is watching at Giotto painting the *Sermon to the birds*":

MANIFEST (`see`, `Experiencer`, `experience`)
DOMINATE (`experience`, `paint`)
`see` (*see*-1, *enrico*, *paint*-1)
`paint` (*paint*-1, *giotto*, *sermon-to-the-birds*)

We have defined in the language the satisfiability, subsumption and instance checking reasoning services, and we have found tractable sound and complete algorithms for these services. In addition, we have studied an extension of the language with other operators (e.g. equality, disjointness in context) and services (e.g. concretion, inheritance and subsumption between concepts with different arity).

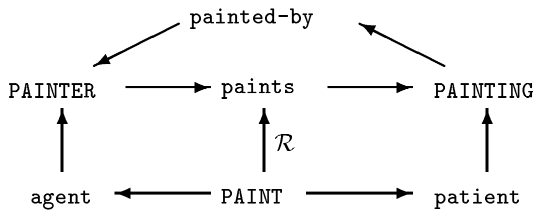

Figure 2: Reification in KL-ONE

We have shown how such a relation-based description logic can be embedded in a KL-ONE-based description logic, like YAK or CRACK. In this way, we solve the problem of reified relations, which was the main obstacle for correctly using KL-ONE-based knowledge representation in lexical semantics. Reification is an operator which allows for both relation-as-role and relation-as-concept interpretations of a binary relation. This operation is crucial for NL applications, e.g. to represent that a noun phrase modified by a prepositional phrase can have the same meaning of the NP modified by a relative phrase. This is the case if the interpretation of the preposition is the same as the one of the relative verb. It is assumed, as it is usual, that prepositions are mapped to roles and verbs to concepts. For example the following sentences should have the same meaning:

Show me a painting of *Giotto's.*
Show me a painting painted by *Giotto.*

In this example – see figure 2 – the concept `PAINT` associated to the verb "paint" reifies the role `paints` associated to the preposition "of", the domain functional role corresponds to the `agent` role of the verb, and the range functional role corresponds to the `patient` role of the verb. This makes the following simplified logical forms equivalent:

$\texttt{show}\ (speaker, f) \wedge \texttt{painting}\ (f) \wedge \texttt{painted-by}\ (f, giotto)$
$\texttt{show}\ (speaker, f) \wedge \texttt{painting}\ (f) \wedge \texttt{paint}\ (e, giotto, f)$
$\texttt{show}\ (speaker, f) \wedge \texttt{painting}\ (f) \wedge \texttt{paints}\ (giotto, f)$

4 Collections, Parts and Plural Quantifiers

Collective entities and collective relations play an important role in natural language. In order to capture the full meaning of sentences like "Giotto and Cimabue painted this fresco", a knowledge representation language should be able to express and reason about *plural entities* – like "Giotto and Cimabue" – and their relationships – like "paint" – with any possible reading (cumulative, distributive or collective).

In [Franconi,1993], an extension of a description logic handling collections and plural quantifiers was introduced. The representational framework outlined in this work is particularly qualified for expressing the logical meaning of natural language utterances containing occurrences of plurals and plural quantifications. An advantage of this formalism is the possibility of reasoning and stepwise refining in the presence of scoping ambiguities. Moreover, many phenomena covered by the Generalized Quantifiers Theory are easily captured within this framework.

In natural language we can distinguish among two different categories of plural entities: classes and collections. Classes are involved in sentences like "Men are persons", where the NP "men" is represented by means of the class predicate MAN:

$$\forall x. MAN(x) \rightarrow PERSON(x).$$

On the other hand, collections are contingent aggregates of objects, and they should be represented as terms instead of predicates, i.e. they should be interpreted at the same level of individuals as single elements of the domain. For example, the logical form of the sentences "The Beatles are John, Paul, George and Ringo" and "John is the leader of the Beatles" is the following:

$\ni(beatles,\ paul),\ \ni(beatles,\ john),$
$\ni(beatles,\ ringo),\ \ni(beatles,\ george),$
$LED\text{-}BY(beatles, john).$

The plural entity *Beatles* is interpreted as a collection, and in the logical form it does not appear as a predicate, but as a term, at the same level as the objects it is composed by. In order to give a meaning to the terms denoting collections, a weakened form of Set Theory – called *Collection Theory* – is adopted. Within the collection theory, *plural quantifiers* are introduced, in order to capture the different readings of a relation when applied to a collection. This approach allows for the representation of *ambiguous* readings, so that in the presence of incomplete information a complete reasoning can still be carried on.

In the following a sample dialogue is given, highlighting the peculiarities of the collection theory in the representation of plurals and plural quantification. The possibility of handling plurals and plural quantifications in a *uniform* and *compositional* way is proper of the collection theory. Each `user` sentence (either informative or query) is followed by its internal simplified[2] logical form; whereas each sentence generated by the `system` is preceded by its internal simplified logical form deduced from the world knowledge and the user request. Please observe that objects with anaphoric reference are prefixed with an exclamation note.

[2] It is simplified for the purpose of understanding better the collection theory.

`U:` "The Beatles are John, Paul, George and Ringo."
$\ni(beatles,\ john),\ \ni(beatles,\ paul),$
$\ni(beatles,\ george),\ \ni(beatles,\ ringo)$

`U:` "Who are the Beatles?"
$\ni(beatles,\ ?X)$

$\ni(beatles,\ john),\ \ni(beatles,\ paul),$
$\ni(beatles,\ george),\ \ni(beatles,\ ringo)$

`S:` "The Beatles are John, Paul, George and Ringo."

`U:` "John is the leader of the pop group."
(collective reading)
$LED\text{-}BY(!PG, john),\ POP\text{-}GROUP(!PG),$
$!PG = beatles$

`U:` "They were born in Liverpool."
(distributive reading)
$\lhd BORN\text{-}IN(!T,\ liverpool),\ !T = beatles$

`U:` "Where was the leader of the group born?"
$BORN\text{-}IN(?X,\ ?Y),\ LED\text{-}BY(!G, ?X),$
$!G = beatles$

$BORN\text{-}IN(john,\ liverpool)$

`S:` "John was born in Liverpool."

`U:` "The Beatles sing 'Yesterday'."
(cumulative reading)
$\unlhd SING(beatles,\ yesterday)$

`U:` "They sing the song all together."
(collective reading)
$SING(!T,\ !S),\ SONG(!S),$
$!T = beatles,\ !S = yesterday$

`U:` "Does John and somebody else sing 'Yesterday'?"
(cumulative reading)
$\unlhd SING(!E,\ yesterday),\ \ni(!E,\ john),\ \ni(!E,\ ?X),$
$PERSON(?X)$

$SING(!E,\ yesterday),\ \ni(!E,\ john),\ \ni(!E,\ paul),$
$\ni(!E,\ george),\ \ni(!E,\ ringo)$

`S:` "John, Paul, George and Ringo sing 'Yesterday' all together."

`U:` "It is true that at most three persons are singing the song all together?"
(collective reading)
$(\leq 3 \ni PERSON)(!F),\ SING(!F,\ !S),$
$!S = yesterday$

$\perp$ $(inconsistency)$

S: "No, it is false."

U: "How many persons at least are singing 'Yesterday'?"

(collective reading)

$(\geq ?X \ni PERSON)(!Q),\ SING(!Q,\ yesterday),\ \ni(!Q,\ ?Y)$

$(\geq 4 \ni PERSON)(!Q),\ SING(!Q,\ yesterday),\ \ni(!Q,\ john),\ \ni(!Q,\ paul),\ \ni(!Q,\ george),\ \ni(!Q,\ ringo)$

S: "There are at least four persons singing 'Yesterday': they are John, Paul, George and Ringo."

In this framework a way to include a theory of parts (mereology) is also presented, allowing for a lattice-theoretical approach to the treatment of plurals. A mereological version of the collection theory has also been applied to model the structure of *events* and *processes* in the domain of tense and aspect in natural language, in order to properly account for perfective and imperfective sentences and for habituals by means of plural quantifiers ranging on collections of events [Franconi *et al.*,1993; 1994]. The basic assumption taken into consideration is that verbal morphology plays a crucial role in specifying the temporal meaning of a sentence.

5 Time, Events and Plans

In a natural language dialogue, an agent can build, execute, simulate, debug and speak of plans and he/she can infer the plans of other agents from their behavior [Cohen and Perrault,1979; Ferguson and Allen,1993]. Plan recognition is used by the system in order to understand the intended goals addressed by the speaker's utterances, by relating the communicated want to the already established ones. The system can infer suitable subgoals and keep track of the temporally evolving situation, according to the initial expectations and the evidence collected so far in the dialog. Plan recognition can also help for solving ambiguities and references, possibly by pragmatically requiring clarification sub-dialogs and providing suggestions from a partial recognition with the creation of new actual communicative goals.

In the papers [Artale and Franconi,1994a; 1994b; 1994c; Artale *et al.*,1994] a way to fully integrate the representation of time, events, plans and states in a description logic is presented. In this work, an action representation in the style of Allen is employed, where an action is represented by describing the time course of events while the action occurs. In this sense, an action is defined by means of temporal constraints on the world states, which pertain to the action itself, and on other more elementary actions occurring over time. A distinction between action types and individual actions is supported by the formalism. Plans are seen as complex actions whose properties possibly change with time. In this environment we exploit the *subsumption* calculus as the main inference tool for managing collections of action types. Given a set of observations of individual actions in the world the system is able to recognize which type of action has taken place at a certain time interval; this task is known as *recognition*. Action types are organized in a subsumption-based plan taxonomy, which can play the role of a plan library to be used for plan retrieval and plan recognition tasks. In this way, we have refined the concept of what is currently called *plan recognition*, by splitting it into the different tasks of *plan description classification* and *specific plan recognition with respect to a plan description*.

Such a representation language can be useful also for the reasoning on plans required by natural language based presentation systems. In the $\mathcal{PPP}$ project [Andre *et al.*,1993] – developed at DFKI, Saarbrücken – an interactive multi-media presentation paradigm is explored with the aim of building a system capable of communicating with an human-being. It emulates the multi-modal interaction between humans supporting user interaction by taking advantage of hyper-media techniques. In particular, in the $\mathcal{PPP}$ system the user can interrupt the system and ask questions about the presentation already generated and change the level of detail or the speed of the current presentation. This system relies heavily both on plan generation, since it should be able to plan presentations and their temporal coordination, and on plan recognition, predicting the outcome of the execution of a set of actions. An important goal of the $\mathcal{PPP}$ project is to represent the temporal relationships between presentation acts in the framework of description logics. We are able to supply such a uniform representation where both temporal reasoning is incorporated with more general techniques for knowledge management and a formal basis for plan recognition is presented.

6 Prototypes

In the research project about Prototypes [Franconi *et al.*,1992] the problem of instance recognition within an extended hybrid knowledge representation system is addressed. Structural aspects of concepts are represented at two separate levels, the terminological and the prototypical; individuals are expressed in the object-oriented assertional component. The hybrid reasoning mechanism recognizes the type of the individuals with respect to the terminology, making use of reasoning with prototypes.

A prototype is such for a certain class; some classes may not have a prototype – e.g. ideas, defined concepts – but many other classes are definable only on a prototypical base – e.g. natural kinds. Basic ideas are shared with the so called Dual Theory about the mental representation of concepts. Within this theory concepts have a twofold representation: a "core description", useful for compositional meaning, and an "identification procedure" for typical instance recognition. Our own realization of such a distinction is that the core strictly defines the necessary and sufficient properties for the concepts (only the necessary ones in the case of primitive concepts), while the identification procedure is a similarity mechanism that works over a collection of perceptual and functional properties. We call such a collection the *prototype* for that concept. Within the identification procedure a "similarity model" is introduced that describes the probability rating that an object belongs to a class, supported by the similarity that the object shares with the prototype of that class.

The typical problem we want to solve is the recognition of an instance member of a natural kind class: is Tweety a bird? A bird is strictly defined using only the necessary properties that every instance of bird must have, while sufficient conditions are missing – i.e. it is a primitive concept. Therefore we cannot ever conclude undeniably that Tweety is a bird. Unless an explicit stated membership in the class bird is present in the information describing Tweety, this fact can not be derived from the terminological knowledge. Sufficient conditions must instead be represented in the prototypical part of knowledge regarding birds. The reasoning part of the prototypical component derives the type for Tweety with a similarity mechanism, comparing the description of the instance with the prototype. If that similarity match succeeds (i.e. it reaches a given threshold), it is possible to assume that, even if we can not be one hundred percent confident, Tweety is a bird, since it is similar to a typical bird.

7 Beliefs

The work on beliefs is the attempt to import into the hybrid framework the ideas about *relevant beliefs* of [Ballim and Wilks,1990]. The goal is to model an artificial agent — the system — which reasons subjectively about the beliefs of other agents in communication with him, in addition to its own beliefs.

The knowledge base has been partitioned into *viewpoints* each one representing a set of complex nested beliefs, i.e. what the system believes the agent `A` believes the agent `B` believes ... about some topic. Topics are simply individual descriptions (or, more generally, ABox propositions) present in the viewpoint. A topic is *believed with respect a viewpoint* if it is logically implied by the knowledge directly stated in the viewpoint or if it is entailed by *ascription*. The ascription mechanism tests the truth value in the "preceding" viewpoints according to a "particular" order; the process fails if at some point a contradiction is detected. The *relevant beliefs* theory presents a method concerning the ascription mechanism for determining whose beliefs are relevant in generating nested beliefs and in what order are they relevant.

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