Building Models for Bridges

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Abstract

Bridging reference resolution presupposes world knowledge coded in some declarative form as well as inferencing methods capable of reasoning on the basis of this knowledge. Furthermore, in order to make bridging reference resolution to become feasible and practicable, the availability of domain knowledge at a large scale as well as of powerful and robust inferencing techniques seems crucial. In this paper I attempt to show how bridging reference resolution can be made feasible by exploiting ontologies developed within the context of the Semantic Web as well as model building techniques. For this purpose I present a DRT-based approach combining these two very promising elements.

1 Introduction

In this paper I understand *bridging* in line with Asher et al. ([2]) as "the inference that two objects or events that are introduced in a text are related in a particular way that isn't explicitly stated". Here follow some examples [1] taken from Clark ([9]):

Example 1.1 I walked into <u>the room</u>. **The chandeliers** sparkled brightly.

Example 1.2 I met <u>two people</u> yesterday. **The woman** told me a story.

Example 1.3 John was <u>murdered</u> yesterday. **The murderer** got away.

In all three cases, the referring definite description is related to the antecedent in a way which is not explicitly given. The relations are *part-of*, *member* and *agent* respectively. The examples clearly show that world knowledge plays a crucial role in the resolution of bridging references. However, if world knowledge should be exploited by a system resolving bridging references, it certainly has to be available in a declarative and machine-readable

[1] In the examples given in this paper, the referring expression is typed in bold face and the antecedent is underlined.

form. This seems in fact a bottleneck as knowledge coded in a declarative form is certainly rare.
In this context, the Semantic Web could represent a valuable resource making large-scale bridging reference resolution feasible. The aims of the Semantic Web as envisioned in [4] are twofold. On the one hand, its aim is to provide the next generation web in which information is not only understandable for people, but also for machines. On the other hand, the aim is to make tools and services interoperable. However, understanding and interoperability are only possible if the involved partners commit to the same underlying conceptualization of the world. For this purpose, the Semantic Web intends to make use of ontologies as abstract and formal conceptualizations of a certain domain to which parties have to commit in order to exchange information between each other. Thus, the success of the Semantic Web is directly coupled with the large-scale availability of domain ontologies. In consequence, if the Semantic Web initiative is successful, a wide range of machine-readable ontologies will be available for their exploitation by natural language understanding systems in general and bridging reference resolution in particular. But even assuming that ontologies are available at a large scale, there still remains the question how this knowledge can be used. For this purpose, some type of inferencing is definitely necessary. As mentioned in [5] and [6], theorem provers and model builders have matured in the last years such that their use within natural language processing systems starts getting a practical option. In this paper I present a DRT-based approach to bridging reference resolution making use of model building techniques in order to exploit knowledge available in form of ontologies. The paper is organized as follows: In section 2, I first discuss some related work. Then, section 3 describes the ontological model underlying this work and section 4 presents the actual approach to bridging reference resolution. Finally, I give a conclusion and mention some further work.

2 Related Work

In [9], Clark makes a distinction between forward and backward inferences and suggests that bridging reference resolution should be based on 'backward' inferences because they are usually determinate. The view underlying the work presented here is that neither backward nor forward inferences on their own are enough for the purpose of bridging reference resolution. Considering example 1.1, it is for instance the case that neither the existence of a room implies the existence of a chandelier nor a chandelier necessarily belongs to a room, but definitely every room has a lamp and a chandelier is some sort of lamp. Thus, the view argued for in this paper is that the interplay between forward inferences from the potential antecedent as well as from the referent is the key to a successful resolution of bridging references.
However, many researchers have neglected this aspect. In Bos et al. ([7]),

anaphors are for example linked to a suitable[2] element of the coercively accommodated qualia structure of some accessible DRS such that the bridging reference resolution process is essentially driven by the qualia structure of the antecedent, which can be seen as a kind of forward inference. In the abductive framework of Hobbs et al. [14], the resolution of example 1.1 is only possible due to a rather awkward modeling of the fact that chandeliers are some specific type of lamps as follows: $\forall x(lamp(x) \wedge has\_branches(x) \rightarrow chandelier(x))$[3]. In contrast, Piwek et al.'s approach ([20]) successfully accounts for the bridging reference in 1.1 given the world knowledge that rooms have lamps and that chandeliers are a special type of lamps. In particular, Piwek et al. rephrase Van der Sandt's approach to presupposition projection in terms of Constructive Type Theory (CTT). In their approach the definite description "the chandelier" introduces a gap for which has to be proved that its type is *chandelier*. This is accomplished by inferring that the room which John entered contains an entity which is a lamp and thus binding part of the presupposition. The rest of the presupposition is satisfied by accommodating that the lamp is in fact a chandelier ([20]).

In [8], I already showed how a simple inference mechanism based on General Modus Ponens (GMP) ([17]) can be used to account for bridging references in which some antecedent is referred to in a (taxonomically) more general way as well as in which the anaphor refers to an entity which can be ontologically inferred from some antecedent.

In this paper I take another direction and show how model builders can be used to account for the interplay between forward inferences from the antecedent as well as the referent. In fact, the approach presented here is in line with the proposal in [12] to use minimal models to resolve definites. The main differences are certainly that this paper reformulates Gardent et al's approach in DRT and furthermore explores how world knowledge available in form of ontologies in the context of the Semantic Web can be integrated into such an approach in a systematic way.

3 The Ontological Model

Currently, in the Semantic Web there are a number of co-existing standards such as RDF(S), DAML+OIL, or more recently also OWL[4], in order to formalize and exchange ontologies. In this paper I will basically adhere to the ontological model presented in [10]. However, I will extend this model to include some features of OWL in order to specify the minimal and maximal cardinality of relations as well as to state that two concepts are disjoint or that a certain concept is the disjoint union of some concepts. Furthermore, I will also include one feature which is currently beyond the OWL formalism,

[2] See [7] for a definition of suitability.
[3] Hobbs et al. use *light* instead of *lamp*.
[4] See http://www.w3.org/TR/owl-ref

i.e. the possibility of stating that two relations are disjoint. The ontological model underlying this work now looks as follows:

Definition 3.1 [Ontology] An ontology is a structure

$$O := (C, \leq_C, R, \leq_R, \sigma, \delta_C, \delta_R, \gamma, f_{min}, f_{max})$$

consisting of

(i) two disjoint sets C and R called *concept identifiers* and *relation identifiers* respectively,

(ii) a partial order $\leq_C$ on C called *concept hierarchy* or *taxonomy*,

(iii) a function $\sigma : R \rightarrow C \times C$ called *signature*[5],

(iv) a partial order $\leq_R$ on R called *relation hierarchy*, where $r_1 \leq_R r_2$ implies $\pi_i(\sigma(r_1)) \leq_C \pi_i(\sigma(r_2))$ for each $1 \leq i \leq |\sigma(r_1)|$,

(v) two symmetric relations $\delta_C : C \rightarrow C$ and $\delta_R : R \rightarrow R$ specifying which concepts or relations are respectively pairwise disjoint,

(vi) a relation $\gamma : C \rightarrow 2^C$ stating that a concept is the disjoint union of certain concepts

(vii) a function $f_{min} : R \rightarrow N$ assigning a minimal cardinality to relations

(viii) a function $f_{max} : R \rightarrow N$ assigning a maximal cardinality to relations.

Furthermore, the model in [10] also supports the inclusion between ontologies in the sense that ontologies can refer to concepts of more general ones. In fact, in the context of the Semantic Web, people are not expected to develop new ontologies from scratch but to create specific ontologies for their domain of interest by reusing concepts from more general ontologies. In this line, I will assume an already existing top level ontology stating the existence of basic types such as events, states, entities, sets of entities as well as roles, i.e. entities whose existence is dependent on time, a certain situation or a certain world.

From a logical point of view, ontologies are logical theories ([13]). In the following, I will show how an ontology as formalized above can be translated into a corresponding first order logical theory T_O. When defining such a translation, it is important to keep in mind that the aim of this paper is to resolve bridging references by using minimal model building techniques. Thus, a main concern is certainly to avoid that entities which are from an ontological point of view incompatible are computed as coreferring by the model builder. The translation of an ontological structure as defined above into a logical theory is given by the following schemas:[6]

(i) $(\forall x\ c_1(x) \rightarrow c_2(x)) \in T_O\ if\ c_1 <_C c_2$ (*concept subsumption*)

[5] Here we actually restrict the model to binary relations.

[6] In what follows, $<_C$ will denote the direct sub-/superconcept relation and $<_R$ the direct sub-/super-relation relation.

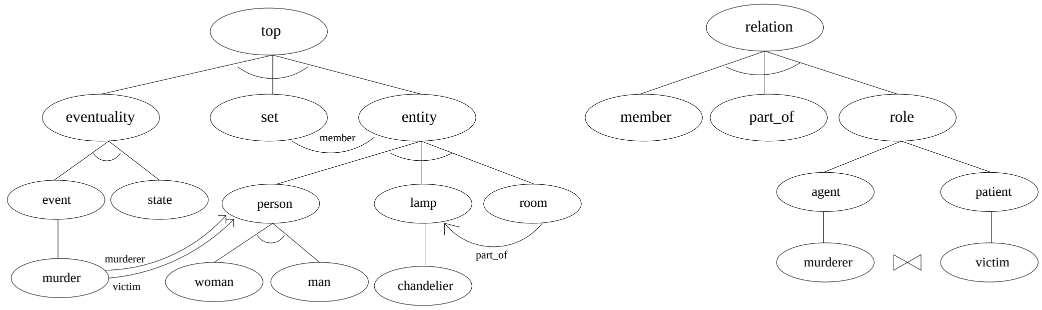


Fig. 1. Example Ontology

(ii) $(\forall x, y\ r_1(x,y) \rightarrow r_2(x,y)) \in T_O\ if\ r_1 <_R r_2$ (*relation subsumption)*

(iii) $(\forall x\ c_1(x) \rightarrow \neg c_2(x)) \in T_O\ if (c_1, c_2) \in \delta_C$ (*disjoint concepts*)

(iv) $(\forall x, y\ r_1(x,y) \rightarrow \neg r_2(x,y)) \in T_O\ if\ (r_1, r_2) \in \delta_R$ (*disjoint relations*)

(v) $(\forall x\ (c(x) \rightarrow (c_1(x) \vee ... \vee c_n(x))) \wedge (c_1(x) \rightarrow \neg(c_2(x) \vee ... \vee c_n(x))) \wedge ... \wedge (c_n(x) \rightarrow \neg c_1(x) \vee ... \vee c_{n-1}(x))) \in T_O\ if\ \gamma(c) = \{c_1, ... c_n\}$
(*disjoint concept union*)

(vi) $(\forall x, y\ r(x,y) \rightarrow c_1(x) \wedge c_2(y))\ if\ \sigma(r) = (c_1, c_2)$ (*relation signature*)

(vii) $(\forall x\ \ c_1(x) \rightarrow \exists y\ (c_2(y) \wedge r(x,y))) \in T_O\ \ if\ r \in R \wedge \sigma(r) = (c_1, c_2) \wedge f_{min}(r) > 0$ (*necessary conditions*) [7]

Thus, the concept hierarchy $<_C$ and the relation hierarchy $<_R$ are translated into corresponding subsumption axioms. Furthermore, the disjointness between concepts and relations as well as the fact that a concept is the disjoint union of certain concepts are axiomatized. The *relation signature* axiom poses the corresponding type restrictions on the arguments of a relation. Finally, the relations in R with a minimal cardinality $f_{min} > 0$ are translated into *necessary condition* axioms in the sense that the existence of an instance of the first concept implies the existence of an instance of the second concept together with the corresponding relation holding between them. Let's now consider a sample ontology which will be used to illustrate the application of the approach presented in this paper to the resolution of examples 1.1-1.3. It is depicted in figure 1. The left and right trees represent the concept and the relation hierarchy respectively. The nodes thus stand for concepts and relations, while the lines represent the taxonomic relations $<_C$ and $<_R$. The labeled arcs between concepts represent relations. Relations with a cardinality $f_{min} > 0$ are represented as arrows. The arcs under a concept express that it is the disjoint union of all its subconcepts. The $\bowtie$ symbol expresses that two concepts or relations are pairwise disjoint. The corresponding logical theory now looks as follows: [8]
$T_O = \{$

[7] In this paper I don't give the complete axiomatization for $f_{min} = n$ or $f_{max} = n$. The complete axiomatizations can be found for example in [3].
[8] The *top* concept as well as the most general *relation* are omitted.

$\forall x\ (eventuality(x) \rightarrow \neg(entity(x) \vee set(x)))$,
$\forall x\ (entity(x) \rightarrow \neg(eventuality(x) \vee set(x)))$,
$\forall x\ (set(x) \rightarrow \neg(eventuality(x) \vee entity(x)))$,
$\forall x\ (eventuality(x) \rightarrow (event(x) \vee state(x)))$,
$\forall x\ (state(x) \rightarrow \neg event(x))$, $\forall x\ (event(x) \rightarrow \neg state(x))$,
$\forall x\ (entity(x) \rightarrow lamp(x) \vee room(x) \vee person(x))$,
$\forall x\ (lamp(x) \rightarrow \neg(room(x) \vee person(x)))$,
$\forall x\ (room(x) \rightarrow \neg(lamp(x) \vee person(x)))$,
$\forall x\ (person(x) \rightarrow \neg(lamp(x) \vee room(x)))$,
$\forall x\ (person(x) \rightarrow woman(x) \vee man(x))$
$\forall x\ (woman(x) \rightarrow \neg man(x))$, $\forall x\ (man(x) \rightarrow \neg woman(x))$
$\forall x\ (state(x) \rightarrow eventuality(x))$, $\forall x\ (event(x) \rightarrow eventuality(x))$,
$\forall x\ (murder(x) \rightarrow event(x))$, $\forall x\ (chandelier(x) \rightarrow lamp(x))$,
$\forall x\ (room(x) \rightarrow entity(x))$, $\forall x\ (woman(x) \rightarrow person(x))$,
$\forall x\ (man(x) \rightarrow person(x))$, $\forall x\ (person(x) \rightarrow entity(x))$,
$\forall x, y\ (member(x, y) \rightarrow set(x) \wedge entity(y))$,
$\forall x, y\ (part\_of(x, y) \rightarrow entity(x) \wedge entity(y))$,
$\forall x, y\ (agent(x, y) \rightarrow event(x) \wedge entity(y))$,
$\forall x, y\ (patient(x, y) \rightarrow event(x) \wedge entity(y))$,
$\forall x, y\ (murderer(x, y) \rightarrow murder(x) \wedge person(y))$,
$\forall x, y\ (victim(x, y) \rightarrow murder(x) \wedge person(y))$,
$\forall x, y\ (murderer(x, y) \rightarrow agent(x, y))$,
$\forall x, y\ (victim(x, y) \rightarrow patient(x, y))$,
$\forall x, y\ (patient(x, y) \rightarrow role(x, y))$, $\forall x, y\ (agent(x, y) \rightarrow role(x, y))$,
$\forall x, y\ (murderer(x, y) \rightarrow \neg victim(x, y))$,
$\forall x, y\ (victim(x, y) \rightarrow \neg murderer(x, y))$,
$\forall e\ (murder(e) \rightarrow \exists\ m(person(m) \wedge murderer(e, m)))$
$\forall e\ (murder(e) \rightarrow \exists\ v(person(v) \wedge victim(e, v)))$
$\forall r\ (room(r) \rightarrow \exists\ l(lamp(l) \wedge part\_of(r, l)))$ [9] $\}$

4 Model Building for Bridging Reference Resolution

For the sake of completeness, I will first define what is meant by a model and furthermore by a minimal model. First of all, an interpretation of a logical theory T is a structure (D, I) that describes how the symbols of the theory are interpreted. In particular, D is a non-empty set of entities and I a function which maps function and relation symbols in T to relations of appropriate arrity in D and constant symbols to elements in D. An interpretation is

[9] Defining a room as always having a lamp is definitely a too strong assumption. However, such an axiomatization will do for the purposes of this paper. In general, we would either state that most rooms have lamps (at least one!) or formulate this fact in a non-monotonic way, i.e. normally rooms have lamps.

moreover a model for a logical theory T if it makes the theory true with regard to the standard first-order semantics. Furthermore, a minimal model is a model whose size is minimal, i.e. there is no other model (D', I') such that $|D'| < |D|$. It is important to mention that following this definition a logical theory can have more than one minimal model. Moreover, it is important to stress that here we are not interested in Herbrand models as their domain is usually infinite due to skolemization if one formula of the logical theory contains at least one existentially quantified variable. However, there is certainly the possibility of considering models which are bisimilarly equivalent to Herbrand models ([21]).

Before formally defining how a model builder can be integrated into the bridging reference resolution process, it should be mentioned that the approach presented here is in line with Van der Sandt ([22]) and Bos et al. [7] in the way anaphora resolution works. Unresolved anaphoric expressions will be represented by α-marked DRSs. A new DRS containing an α-marked DRS will be merged with the main-DRS for the discourse processed so far as in standard DRT and only after merging resolved [10]. When an α-marked DRS is resolved, the α-mark will disappear. Only when the main-DRS does not contain any unresolved DRSs, will it be interpretable as in standard DRT ([16]). The reason for using a DRT-based approach is that due to the accessibility relation between DRSs we restrict the resolution to accessible antecedents.

After these clarifications, we are now ready to formally introduce the *RESOLVE* operation. It takes the main-DRS K_m and the unresolved DRS K_α as input and returns a set of DRSs where K_α is resolved. In the following, $\leq$ will denote the subordination relation between DRSs and is basically introduced to guarantee accessibility (consult [16] for the relation between accessibility and subordination). The operation $K_1[K_2/K_3]$ means that the DRS K_2 is substituted by the DRS K_3 in the DRS K_1.

Definition 4.1 [Resolution]

$$
\begin{aligned}
RESOLVE(K_\alpha, K_m) = \{K'_m |\ & K_\alpha \leq K_1 \wedge \alpha : K_\alpha \in C(K_2) \wedge \\
& \text{(D,I) is a minimal model for } (T_O \wedge [K_1 \oplus K_\alpha]_{PL_1}) \wedge \\
& U(K_3) = U(K_2) \wedge C(K_3) = C(K_2) - \alpha : K_\alpha \wedge \\
& U(K_4) = U(K_\alpha) \cup D \wedge C(K_4) = C(K_\alpha) \cup I \wedge \\
& K'_m = K_m[K_1/K_1 \oplus K_4][K_2/K_3]\}
\end{aligned}
$$

where $[K]_{PL_1}$ is the translation of a DRS K to predicate logic as given in [16]. Thus, the minimal model (D,I) is accommodated at the level of K_1 such that the relation between the resolved α-marked DRS and the antecedent becomes explicit. Note that the DRS K_1 is somehow 'free' in the above definition. This corresponds to the fact that all accessible DRSs could potentially be an antecedent for the anaphoric expression. In consequence, the model

[10] Certainly, the most deeply embedded α-marked DRS has to be processed first, but this aspect will not be discussed any further. The interested reader is referred to Van der Sandt ([22]).

builder is called for every accessible DRSs in the main DRSs K_m.
Now what if no minimal model can be computed? This is certainly a possibility which has to be taken into account as for full first-order logics model generation is incomplete, i.e. given a satisfiable first-order theory, there is no method that can always find a model. As a consequence, some 'repair strategy' is needed for the case when no model can be found. The usual way to handle model generation incompleteness is to assign a maximal processing time to the minimal model builder. After this time has elapsed, if no model has been computed, the bridging reference will simply be accommodated as specified by the following ACC operation:

Definition 4.2 [Acommodation]

$$
\begin{aligned}
ACC(K_\alpha, K_m) = \{K'_m |\ & K_\alpha \leq K_1\ \wedge \alpha : K_\alpha \in C(K_2) \wedge \\
& U(K_3) = U(K_2) \wedge C(K_3) = C(K_2) - \alpha : K_\alpha \wedge \\
& K'_m = K_m[K_1/K_1 \oplus K_\alpha][K_2/K_3]\}
\end{aligned}
$$

Following van der Sandt ([22]), accommodation should be preferred as high as possible. However, it is also restricted by certain constraints: it should not introduce free variables, it should be consistent, i.e. not introduce any contradictions, and informative in the sense that the accommodated material is not entailed by the preceding context. In [5], Blackburn et al. present an approach in order to guarantee consistency and informativity by using theorem provers which would fit nicely into the above definition.
It just remains to clarify how bridging reference resolution can be made determinate. Certainly, the above *RESOLVE* operation returns for each possible (accessible) antecedent a set of possible resolutions of the α-marked DRS corresponding to the different minimal models.
Certainly, the most recent antecedent should be preferred, but then there still remains the problem of choosing a certain resolution given a certain antecedent. Furthermore, *linking* should be preferred over *bridging* and *bridging* over *accommodation* (compare [7]). In addition, according to Clark [9], knowledge resources should be used as frugal as possible in the sense that the resolution requiring the fewest assumptions should be chosen. When using minimal models for resolving definite descriptions, the preference of *linking* and *bridging* over *accommodation* is implicit as a minimal model will never contain more individuals than necessary ([12]). On the other hand, the preferences of *linking* over *bridging* and of resolutions requiring the fewest assumptions are closely related and can both be accounted for by integrating an appropriate notion of salience which allows to distinguish how "important" the various objects in the discourse universe are. In this sense, the **salience** of an object is defined as the availability of an entity in the discourse universe for (anaphoric or definite) reference ([1]). Consider for instance the following example:

Example 4.3 Mary loves Peter. She likes especially **the eyes**.

Furthermore, let's assume that our world knowledge contains the fact that every person has eyes and that every person has a mother. Then certainly we will have an infinite number of minimal models in which **the eyes** belong respectively to Peter, to Peter's mother, to Peter's mother's mother, ... Thus our theory needs to explain why Peter's eyes are more salient than his mother's eyes. An elegant solution would be to make use of a tableaux-based model builder as described in [19] which takes into account the salience of domain individuals. In line with Kohlhase et al.([19]), the correct reading of the above sentence can be achieved by modifying our domain knowledge rules as follows:

$$\forall X\ person(X) \rightarrow \exists Y_{X/2}\ eyes(Y) \wedge part\_of(X,Y)$$
$$\forall X\ person(X) \rightarrow \exists Y_{X/2}\ woman(Y) \wedge mother(X,Y)$$

Thus in our example Peter's eyes would have half the salience of Peter and Peter's mother would also be half less salient than Peter. Peter's mother's eyes would accordingly be four times less salient than Peter's eyes such that the example would be resolved correctly. It is important to mention that the preference of *linking* over *bridging* is a special case of preferring the solution maximizing salience.
However, it should also be mentioned that the specification of the salience of expressions in the syntax-semantics interface and in the world knowledge is still an open problem. However, salience is not the only criterion to prefer one solution to another. Certainly, the discourse structure also plays an important role. Asher et al. ([2]) for example prefer the solution maximizing the discourse coherence. For this purpose, they assume a total ordering on the discourse relations they consider. Other important factors which definitely also have an influence on the choice of the appropriate solution are prosodic as well as syntactic information.

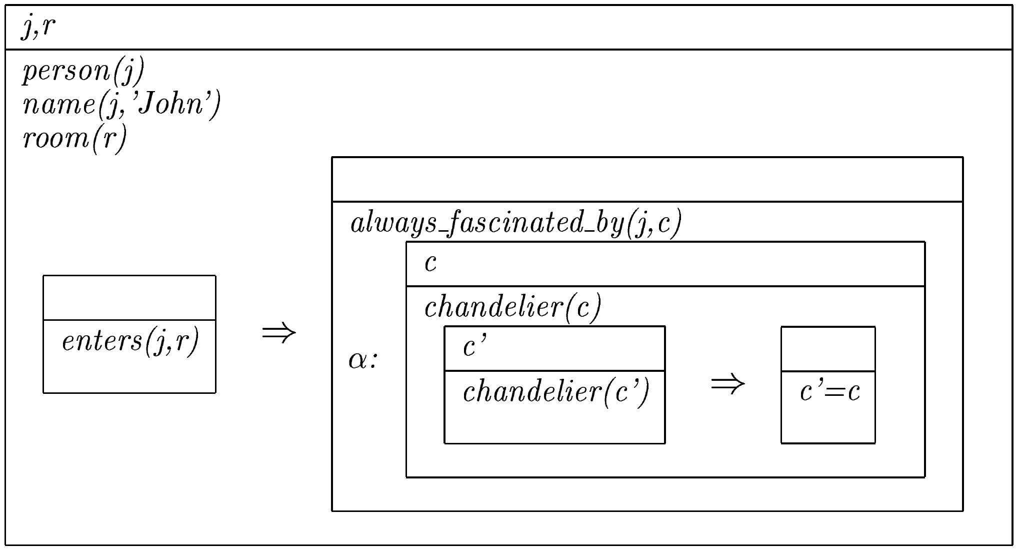
4.1 Application to Examples

In this section I show how the approach described above can be applied to resolve the bridging references in the introductory examples. In particular, I will consider the following variant of example 1.1 in order to show that the accommodation of minimal models into the DRS works also for complex DRS conditions:

Example 4.4 When John enters the room, he is always fascinated by **the chandelier**.

It is important to mention that in line with [2] in this paper I will assume that the uniqueness condition holds for definites. Certainly, this assumption is not without problems ([12], [16]) and the assumption of a unique property P as in [12] seems definitely more appropriate. However, I will abstract from these questions as a proper analysis of definites is certainly out of the scope of this paper. Let's now assume the DRS K_1 (see below) for the above discourse [11] [12].

K_1:



Thus according to the RESOLVE operation defined above, we have to find a minimal model for the following formula [13]:

$(F_1 = T_O \wedge \exists j, r, c\ person(j) \wedge name(j,' John') \wedge room(r) \wedge chandelier(c) \wedge$
$\forall c'\ (chandelier(c') \rightarrow c' = c))$

Now the minimal model (D_1, I_1) for F_1 is as follows [14]: $D_1 = \{d_1, d_2, d_3\}$
$I_1 = \{d_1 = j, d_2 = r, d_3 = c, person(d_1), name(d_1,' John'), room(d_2), lamp(d_3),$
$chandelier(d_3), part\_of(d_2, d_3)\}$

Finally, we accommodate the minimal model and yield the resolved DRS K_1' (see below) where the definite description "the chandelier" has been successfully resolved as being *part_of* the room.
Let's now discuss the next example:

Example 4.5 I met two people yesterday. **The woman** told me a story.

First, we will assume the DRS K_2 (see below) for the above discourse. [15] [16]

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[11] The pronoun *he* is assumed as already resolved to *John*.

[12] I assume that all events are modeled much in the same way as the *murder* event in section 3, in the sense that they will be reified alla Davidson and the ontology introduces their implicit arguments together with the corresponding thematic roles. However, I will abstract from this representation where it is not relevant.

[13] In order to illustrate how a minimal model can be accommodated we use a slightly different notation for minimal models than for example in [6].

[14] I will omit predicates corresponding to basic types, i.e. *event*, *entity* etc. in the minimal models whenever they are not relevant.

[15] In this and in the following example we will abbreviate the uniqueness condition stating that x is the only individual with property P as *uniq(P,x)*

[16] The solution to represent sets adopted in this example is certainly not a general solution

$$K_1' : \begin{array}{|l|}\hline j,r,c,d_1,d_2,d_3 \\ \hline person(j) \\ name(j,\text{'John'}) \\ room(r) \\ chandelier(c) \\ d_1 = j \\ d_2 = r \\ d_3 = c \\ person(d_1) \\ room(d_2) \\ lamp(d_3) \\ chandelier(d_3) \\ part\_of(d_2,d_3) \\ \begin{array}{|c|}\hline \\ \hline enter(j,r) \\ \\ \hline \end{array} \Rightarrow \begin{array}{|c|}\hline \\ \hline always\_fascinated\_by(j,c) \\ \\ \hline \end{array} \\ \\ \hline \end{array}$$

So, we need to find a minimal model for the formula:

$$F_2 = T_O \wedge \exists p, p_1, p_2, w \ (I\_met\_yesterday(p) \wedge set(p) \wedge member(p_1, p) \wedge person(p_1) \wedge member(p_2, p) \wedge person(p_2) \wedge \neg p_1 = p_2 \wedge told\_me\_a\_story(w) \wedge woman(w) \wedge \forall x \ (woman(w') \rightarrow w' = w))$$

In fact, we yield the following two (symmetric) models (D_2, I_2) and (D_2', I_2'):
$D_2 = \{d_1, d_2, d_3\}$
$I_2 = \{d_1 = p, d_2 = p_1, d_3 = p_2, d_2 = w, I\_met\_yesterday(d_1), set(d_1), member(d_2, d_1), member(d_3, d_1), person(d_2), person(d_3), told\_me\_a\_story(d_2), woman(d_2), man(d_3)\}$
$D_2' = \{d_1, d_2, d_3\}$
$I_2' = \{d_1 = p, d_2 = p_2, d_3 = p_1, d_2 = w, I\_met\_yesterday(d_1), set(d_1), member(d_2, d_1), member(d_3, d_1), person(d_2), person(d_3), told\_me\_a\_story(d_2), woman(d_2), man(d_3\}$

Certainly, both models are from a linguistic point of view equivalent, such that it makes actually no difference to choose one or the other. Assuming that we choose the first model, we will get the resolved DRS K_2' where the minimal model is accommodated and the definite description "the woman" has been resolved as being *member* of the set of (two) people mentioned in the first sentence. Furthermore, because of the uniqueness of the woman and because of the fact that *person* is the disjoint union of *man* and *woman*, the other person in the set is inferred to be a man.

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to the problem of representing the cardinality of sets; nevertheless, it will suffice for the purposes here.

$$
K_2 : \begin{array}{|l|}\hline
p, p_1, p_2 \\ \hline
I\_met\_yesterday(p) \\
set(p) \\
member(p_1, p) \\
person(p_1) \\
member\ (p_2, p) \\
person(p_2) \\
\neg p_1 = p_2 \\
\begin{array}{|l|}\hline
\\ \hline
told\_me\_a\_story(w) \\
\alpha: \begin{array}{|l|}\hline
w \\ \hline
woman(w) \\
uniq(woman, w) \\
\\ \hline
\end{array} \\
\\ \hline
\end{array} \\
\\ \hline
\end{array}
\qquad
K_2' \begin{array}{|l|}\hline
p, p_1, p_2, w, d_1, d_2, d_3 \\ \hline
I\_met\_yesterday(p) \\
set(p) \\
(...) \\
told\_me\_a\_story(w) \\
woman(w) \\
(...) \\
d_2 = w \\
d_2 = p_1 \\
d_3 = p_2 \\
woman(d_2) \\
man(d_3) \\
d_1 = p \\
member(d_2, d_1) \\
\\ \hline
\end{array}
$$

Now to the last example:

Example 4.6 John was murdered yesterday. **The murderer** got away.

For this discourse we will assume the DRS K_3 (see below). Thus, we have to find a minimal model for the following formula:

$$F_3 = T_O \wedge \exists e, j, e', m\ (murder(e) \wedge person(j) \wedge name(j, 'John') \wedge victim(e, j) \wedge murder(e') \wedge got\_away(m) \wedge murderer(e', m) \wedge \forall m'\ (murderer(e', m') \rightarrow m' = m))$$

The minimal model is: $D_3 = \{d_1, d_2, d_3\}$
$I_3 = \{d_1 = e, d_1 = e', d_2 = j, d_3 = m, murder(d_1), person(d_2), name(d_2, 'John'), victim(d_1, d_2), patient(d_1, d_2)\ got\_away(d_3), person(d_3), murderer(d_1, d_3), agent(d_1, d_3)\}$

Finally, the minimal model is accommodated and the definite description "the murderer" is resolved as being agent of the murder event mentioned in the first sentence.

5 Conclusion and Further Work

In this paper I have presented an approach to bridging reference resolution combining world knowledge coded in form of ontologies as well as model building techniques. In particular I have presented a Van der Sandt-style, DRT-based approach which calls a model builder as a subtask and then accommodates the minimal model into the DRS. The obvious benefit of using DRT is that we only consider accessible DRSs as potential antecedents. The approach has been implemented by reusing the bridging reference resolution approach

K_3:

e,j
$murder(e)$ $name(j,\text{'John'})$ $person(j)$ $victim(e,j)$
[   ] ⇒ $got\_away(m)$ α: [e',m | $person(m)$, $murder(e')$, $murderer(e',m)$, $uniq(murderer,m)$]

K'_3

e,e',j,m,d_1,d_2,d_3
$murder(e)$ $name(j,\text{'John'})$ $victim(e,j)$ $patient(e,j)$ $got\_away(m)$ $murder(e')$ $murderer(e',m)$ $(\ldots)$ $d_3 = m$ $d_1 = e$ $d_1 = e'$ $murderer(d_1,d_3)$

presented in [8] as well as integrating the model builder *MACE*.[17] [18]
Though MACE took around 0.01 seconds to resolve the examples discussed in this paper, one problem of the approach is certainly the fact that model generation is exponential in the size of the universe and thus for larger discourses and ontologies the model builder may take too long to find an answer. Even worse, the model builder is called for each possible and accessible antecedent (compare the *RESOLVE* operation) such that it would be an interesting direction for further research to clarify if it is possible to take into account results from previous calls to the model generator and thus make the whole process more efficient.
Another problem of the approach presented in this paper is that it is not always desirable to have one single model. Consider the following examples:

Example 5.1 I met a German and an American. **The woman** told me a story.

Example 5.2 I met two people. **The Austrian or German woman** told me a story.

In both examples the nationality of the woman should remain underspecified and this is certainly not possible if we have only one single model. Thus, it would be interesting to represent all minimal models in a packed form and draw inferences from this packed representation. For this purpose an assumption-based truth maintenance system (ATMSs) ([11]) seems an interesting option to be explored.
On the other hand, there still remains the question open how to make bridging reference resolution determinate. Though I have mentioned some possibilities

[17] http://www-unix.mcs.anl.gov/AR/mace/
[18] In http://www.aifb.uni-karlsruhe.de/WBS/pci/bridging.mace you will find the logical theory as well as the examples in MACE format.

to accomplish this, it will be necessary to analyze in a systematic way how different linguistic information sources such as salience, discourse structure, prosody or syntax interact to yield one (unique) resolution.
In particular, further research will aim at clarifying and formalizing the strong relation between world knowledge about events, discourse structure and bridging, but without assuming that bridging is merely a byproduct of computing how the sentences of a discourse are connected as in [2]. The following examples motivate this strong relation:

Example 5.3 I left the room. The chandelier sparkled brightly.

Example 5.4 I walked into the room. I could see the sparkling chandelier through the window.

In general, the model presented in this paper seems general enough to be applicable to other types of anaphora. Considering the case of presuppositions which typically are justified in context by a combination of (partial) satisfaction and (partial) accommodation ([15]), it seems plausible to mimic justification through minimal model generation.
Finally, it would also be interesting to explore other inferencing techniques and logics such as F-Logic ([18]) or Description Logics ([3]) for the purpose of bridging reference resolution.

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References

[1] Alshawi, H., "Memory and Context for Language Interpretation," Cambridge University Press, 1987.

[2] Asher, N. and A. Lascarides, *Bridging*, Journal of Semantics **15** (1999), pp. 83–113.

[3] Baader, F., D. Calvanese, D. McGuiness, D. Nardi and P. Patel-Schneider, editors, "The Description Logic Handbook," Cambridge University Press, 2003.

[4] Berners-Lee, T., J. Hendler and O. Lassila, *The Semantic Web*, Scientific American (2001).

[5] Blackburn, P., J. Bos, M. Kohlhase and H. de Neville, *Inference and computational semantics*, in: H. Bunt and E. Thijsse, editors, *Proceedings of the IWCS-3*, 1999, pp. 5–21.

[6] Bos, J., *Exploring model building for natural language understanding*, in: *Proceedings of the 4th International Workshop on Inference in Computational Semantics (ICoS-4)*, 2003.

[7] Bos, J., P. Buitelaar and M. Mineur, *Bridging as coercive accomodation*, in: E. Klein, S. Manandhar, W. Nutt and J. Siekmann, editors, *Working Notes of the Edinburgh Conference on Computational Logic and Natural Language Processing (CLNLP-95)*, 1995.

[8] Cimiano, P., *Ontology driven resolution of bridging references*, in: *Proceedings of the 5th International Workshop on Computational Semantics (IWCS-5)*, 2003.

[9] Clark, H., *Bridging*, in: P. Johnson-Laird and P. Wason, editors, *Thinking, Readings in Cognitive Science*, Cambridge University Press, 1977 pp. 411–420.

[10] E. Bozsak et al., *KAON - Towards a large scale Semantic Web*, in: *Proceedings of the Third International Conference on E-Commerce and Web Technologies (EC-Web)* (2002).

[11] Forbus, K. and J. de Kleer, editors, "Building problem solvers," MIT Press, 1992.

[12] Gardent, C. and K. Konrad, *Interpreting definites using model generation*, Journal of Language and Computation **1** (2000), pp. 193–209.

[13] Gruber, T., *Toward principles for the design of ontologies used for knowledge sharing*, in: *Formal Analysis in Conceptual Analysis and Knowledge Representation*, Kluwer, 1993 .

[14] Hobbs, J., M. Stickel, D. Appelt and P. Martin, *Interpretation as abduction*, Artificial Intelligence **63** (1993), pp. 69–142.

[15] Kamp, H., *The importance of presupposition*, in: C. Rohrer, A. Roßdeutscher and H. Kamp, editors, *Linguistic Form and its Computation*, CLSI, 2001 pp. 207–254.

[16] Kamp, H. and U. Reyle, "From Discourse to Logic," Kluwer, 1993.

[17] Kamp, H. and U. Reyle, *A calculus for first order discourse representation structures*, Journal of Logic, Language, and Information **5** (1996), pp. 297–348.

[18] Kifer, M., G. Lausen and J. Wu, *Logical foundations of object-oriented and frame-based languages*, Journal of the Association for Computing Machinery (1995).

[19] Kohlhase, M. and A. Koller, *Towards a tableaux machine for language understanding*, in: *Proceedings of the International Workshop on Inference in Computational Semantics (ICoS-2)*, 2000.

[20] Piwek, P. and E. Krahmer, *Presuppositions in context: constructing bridges*, in: P. Brezillon and M. Cavalcanti, editors, *Formal and Linguistic Aspects of Context*, Kluwer, 1997 .

[21] Stirling, C., *Bisimulation, model checking and other games*, in: *Notes for Mathfit instructional meeting on games and computation*, 1997.

[22] van der Sandt, R. A., *Presupposition: Projection as anaphora resolution*, Journal of Semantics (1992), pp. 333–377.