A first-order account of the relation between bridges, discourse relations and world knowledge

Philipp Cimiano

Institute AIFB, University of Karlsruhe

1 Introduction

The resolution of bridging references is certainly highly interwined with the computation of discourse relations as well as with the integration of world knowledge into the interpretation of a discourse. In what follows we present examples which clearly corroborate this fact:

Example 1.1 *John entered the room. He saw the chandelier sparkling brightly.*

In this example, the resolution of the bridging reference *the chandelier* depends on the discourse relation by which the second sentence is attached to the first. In fact, assuming that we can not see objects in a room if we are not in it, the chandelier can only be linked to the room in the first sentence if the seeing event follows the entering event, i.e. only if the temporal order imposed by the corresponding discourse relation preserves the surface order. In particular, inferring *Narration* or *Result* (cf. [14]) would be consistent with the resolution, while *Explanation* would not. Now let's consider the following example:

Example 1.2 *John entered the room. He saw the chandelier through the window.*

Provided that the window is resolved as being part of the room and assuming that we can only see objects through a window which are not in the same room, the definite description *the chandelier* can only be resolved as belonging to the room if the seeing event precedes the entering of the room the chandelier belongs to. In this case thus *Explanation* would be a valid discourse relation, while *Narration* and *Result* would not.

In the following example this situation is exactly reversed again due to the semantics of 'leave':

Example 1.3 *John left the room. He saw the chandelier sparkling brightly.*

The above examples clearly show how the computation of discourse relations, world knowledge and bridging reference resolution constrain each other.

The following example consisting in a minimal pair also involves temporal aspects and has been discussed in [2] and later in [10]:

Example 1.4 *John arrived at the oasis. The camels <u>are</u> standing under the palms.*

Example 1.5 *John arrived at the oasis. The camels <u>were</u> standing under the palms.*

The point here is that the camels in the second discourse can not be resolved as being the means of transport by which John arrived as the use of the imperfect shows a preference for interpreting the state in the second sentence as temporally overlapping with the arrival (compare [12] and [10]), which would yield an inconsistency as the camels would not be at the oasis as well as be at the oasis at overlapping states. The resolution of the camel as being the means of transport by which John arrived should thus be prohibited by any account of bridging reference resolution. Gardent and Webber [10], when analyzing an example similar to the camel example above – also discussed in [2] – rise the question if the interaction between discourse relations, world knowledge and bridging reference resolution can indeed be captured by first-order means. This paper is an attempt in this direction.

In general we have to conclude that the resolution of a bridging reference has to be consistent with world knowledge as well as with the consequences introduced by certain discourse relations as well as by tense information. In order to model the information flow between bridging reference resolution, world knowledge, tense information and the computation of discourse relations, in this paper we present a declarative first-order account in which bridging reference resolution is a byproduct of building a minimal model of a discourse as in [9] or [7], which thus is also consistent with world knowledge as well as the implications of a certain (inferred) discourse relation. The paper is structured as follows: Section 2 gives a brief overview of related approaches, especially the ones of Gardent et al. [9] as well as Hobbs et al. [11] and Asher et al. [2]. Section 3 discusses why minimal models are an elegant solution to the problem of bridging reference resolution, but also mentions some of the problems involved. Section 4 presents the ingredients of our first-order logical theory modeling the information flow between bridging reference resolution, world knowledge and the computation of discourse relations. Section 5 discusses the examples mentioned in the introduction and Section 6 concludes the paper.

2 Related Work

Gardent and Konrad [9] have proposed resolving definite descriptions as a byproduct of constructing a (minimal) model for the discourse in question. Such an approach has a number of benefits as well as trade-offs which we will discuss in detail in section 3. We are aware of two other approaches concerned with the information flow between bridging reference resolution, world knowledge and bridging reference resolution, i.e. the work of Asher and Lascarides [2] and the abductive framework of Hobbs [11]. The main claim in [2] is that bridging reference resolution is a byproduct of computing the rhetorical structure of a discourse. Their approach is formalized in SDRT and based on four meta-rules driving the resolution of bridging references: i) *If possible use iden-*

tity, ii) *Bridges are Plausible*, iii) *Discourse Structure Determines Bridging*, and iv) *Maximise Discourse Coherence*. The first meta rule (*If possible use identity*) corresponds to the preference in Van der Sandt-style algorithms for resolution to identity (compare [5,6,16]). The second meta-rule (*Bridges are Plausible*) is a constraint stating that the rhetorical structure of the discourse has to make a certain resolution of the bridging reference 'plausible'. The third rule (*Discourse Structure Determines Bridging*) captures the intuition that if the rhetorical relation connecting the relevant discourse segments gives a particular way of resolving the bridging reference, i.e. it makes this resolution 'plausible', then the reference is resolved in that way. Fourth, *Maximise Discourse Coherence* applies when no discourse relation can be inferred and that plausible reference resolution is chosen which maximizes discourse coherence with respect to a partial ordering of the discourse relations. Asher et al. in fact attempt to account for the information flow between reference resolution, world knowledge and discourse structure by the above mentioned metarules. However, there are three main objections to this approach, two theoretical and one pragmatical. On the theoretical side, one problem is that the notion of *plausibility* is not formalized at all and thus it is not clear how this notion interacts with world knowledge to select plausible resolutions. Second, the four rules described by Asher et al. seem somehow 'ad hoc'. What we should aim at is a declarative approach in which the cases specified by the above rules (and possibly others) emerge from deeper principles specified in a declarative form, i.e. a logical theory. On the pragmatic side, there is no tool support for SDRT, the glue logic DICE for computing discourse relations nor a calculus implementing the already mentioned notion of plausibility with respect to world knowledge. Instead, our aim in this paper is to resort to state-of-the-art model building techniques.

The abductive approach of Hobbs in contrast is declarative and in fact very related to the model building process described in [9]. As described in [11], abduction is inference to the best explanation and, as they additionally introduce costs for assuming certain facts, their weighted abduction scheme favors the most economical proof, merging redundancies in order to get a minimal interpretation. In fact, model building behaves in a similar fashion as abduction in the sense that both aim at establishing the most economical explanation for a certain theory. In fact, Hobbs et al. also attempt to account for the connection between bridging reference resolution, discourse structure and world knowledge, but in contrast to [2] this relation emerges from deeper principles, i.e. the preference for minimal/economical interpretations and the principle that every segment of an utterance needs to be discourse connected to another segment. The approach presented in this paper attempts to account for this information flow according to these deeper principles as done in [11] but for the pragmatic reason that model builders are widely available and furthermore becoming very efficient, it adopts the framework of [9] relying on minimal models as most economical interpretations of a discourse. The next section discusses why considering minimal models is indeed an interesting alternative, but also discusses some of the problems involved in this choice.

3 Why minimal models?

Considering bridging reference resolution as a byproduct of constructing a minimal model for an utterance is an elegant solution because of a number of reasons. First, language is a highly redundant as argued in [11] and minimality eliminates these redundancies, thus yielding a canonical or minimal interpretation easier to process. Second, assuming that we are considering models which are domain minimal (cf. [9]), the preference for resolution to identity over accommodation as in van der Sandt-like approaches ([16]) such as [5] and [6] emerges in a principled way. Third, while van der Sandt-style presupposition projection approaches need to perform two steps: (i) projection or resolution and (ii) checking consistency and informativeness, a model building approach as described in [9] resolves the reference and ensures consistency at the same time. Informativeness would then still need to be verified for example by a theorem proover as suggested in [3]. In addition, it allows to account for the information flow between different types of knowledge such as knowledge about discourse relations or world knowledge in a straightforward way as we only have to add corresponding axioms to the underlying theory. The model building process will then take care of the rest, i.e. to construct an interpretation which is consistent will the different types of knowledge included in the logical theory. Furthermore, minimal models are flat structures and can be easily processed as argued in [4] as well as incorporated into other structures such as for example DRSs as shown in [7].
On the pragmatic side another benefit is that first-order model builders are widely available and have been already shown to be useful tools for Natural Language Processing ([4]).
One of the problems involved in using minimal models in order to model bridging reference resolution (and probably other linguistic phenomena) is that there is no difference between linking [5], 'short' and 'long' bridges as all the corresponding models have equal size. In fact, the behavior of a model builder is greedy in the sense that it saturates a logical theory and then comes up with the best explanation for it. In the model itself it is no longer visible how 'easy' or 'complex' – in the number of deduction steps – it was to derive a certain fact from the original theory. However, as argued in [8], people tend to use their resources as frugal as possible. In fact, in order to prevent inferences *ad infinitum*, some notion of cost on each inference step needs to be introduced. For this purpose, Hobbs et al. use their weighted abduction scheme in which the assumption of certain facts implies a certain cost. Koller et al. [13] present a resource-sensitive tableaux-based model builder taking into account the salience of individuals, and in which the application of certain rules modifies (typically decreases) the salience of the individuals (existentially quantified in the consequent) with respect to the antecedent. This issue is certainly out of the scope of this paper, but we will assume a minimal model builder in the lines of Koller et al. as well as a preference of minimal models maximizing salience.

4 Ingredients of the logical theory

The logical theory for which we want to find a minimal model consists of the following parts: i) a description of the input discourse, ii) discourse principles, iii) axioms on discourse relations, iv) tense and temporal axioms, and v) world knowledge. We describe each of these components in the following sections.

4.1 Input discourse

The input discourse constitutes the variable part of the theory as it varies for each discourse we want to analyze. The input description of the discourse in particular states the surface order of the involved events. Let's for example consider example (1), for which the input description looks as follows, where $\prec$ denotes the surface order of events:

$$\exists e, e', j, r, c\ enter(e) \wedge agent(e, j) \wedge patient(e, r) \wedge event(e) \wedge past(e) \wedge perfect(e) \wedge room(r) \wedge see(e') \wedge agent(e', j) \wedge patient(e', c) \wedge state(e') \wedge past(e') \wedge perfect(e') \wedge chandelier(c) \wedge e \prec e'$$

4.2 Discourse Principles

It has been argued especially in Asher et al. [2] and furthermore become the main point in SDRT, that discourse segments need to be connected to previous discourse segments by some rhetorical relation. We axiomatize this in our theory as follows:

Definition 4.1 (Discourse Connectedness)

$$\forall e\ eventuality(e) \rightarrow \exists e'(e' \prec e \wedge eventuality(e') \wedge dconnected(e', e))$$

That means, each event has to be discourse connected to some previously mentioned event (according to the surface order of events). This is in line with the approaches of [11] and [14]. Now we only have to define what *d-connected* means:

Definition 4.2 (Discourse Relations)

$$\forall e, e'\ dconnected(e, e') \leftrightarrow drel(e, e', r_1) \vee ... \vee drel(e, e', r_n)$$

where $r_1 ... r_n$ are constants representing the discourse relations described in [2] such as *Narration, Parallel, Result, Explanation, Elaboration, Background*, etc. So, in contrast to the work in [2] we are treating discourse relations as first-order constants instead of relations.

4.3 Axioms on Discourse Relations

Further, we need to define axioms specifying the spatio-temporal consequences of a given discourse relation. We do this exemplary for three relations: *Narration, Result* and *Elaboration*, where the axioms are basically taken from [2]. The axioms we need for the purposes of this paper are given in Figure 1.

Definition 4.3 (Temporal consequences on narration)
$\forall e, e' \; drel(e, e', narration) \rightarrow e < e'$

Definition 4.4 (Spatial consequences on narration)
$\forall e, e', a \; drel(e, e', narration) \wedge agent(e, a) \wedge agent(e', a) \rightarrow$
$\forall s, s' \; (e \supset\!\subset s \wedge s' \supset\!\subset e' \rightarrow \exists l \; loc(s, a, l) \wedge loc(s', a, l))$

Definition 4.5 (Consequences on Result)
$\forall e, e' \; drel(e, e', result) \rightarrow cause(e, e') \wedge e \supset\!\subset e'$

where $e \supset\!\subset e'$ is defined as follows:

Definition 4.6 (Abut) $\forall e, e' \; e \supset\!\subset e' \rightarrow e < e' \wedge \neg \exists e'' e < e'' < e$

Definition 4.7 (Consequences on Elaboration)
$\forall e, e' \; drel(e, e', elaboration) \rightarrow e' \in prep(e)$

Fig. 1. Axioms on discourse relations

4.4 Tense and Temporal Axioms

Kamp has argued in [12] that the *simple past* – Passe Simple, as he discusses it for French – is typically used to report the successive elements of the main course of action of a story, while the imperfect serves to present the setting in which the action is taking place. In particular, Kamp presents a procedure ([12], p405) describing how a sentence in the perfect or in the imperfect relate to the preceding discourse. The procedure basically states the following: an event reported in the imperfect overlaps with all preceding events in imperfect until the first event reported in the perfect is encountered. The former ones are thus interpreted as describing the circumstances under which the punctual event (reported in the perfect) occurred. This is not the case, for the perfect, for which Kamp claims that a succession of sentences in the perfect convey a similar temporal order of the reported events.
The second principle is probably to strong to be axiomatized (as temporal order does not always correspond to the surface order). Thus, we only axiomatize the first principle on the imperfect. Before, however, we need to introduce the notion of overlap $\oplus$ between eventualities. In fact, we will introduce a function $\oplus_f$ denoting the intersection between two eventualities. Further, we will have a special sign $\perp$ denoting the empty intersection. The corresponding predicate $\oplus_p$ is then defined in terms of $\oplus_f$ as follows:

Definition 4.8 ($\oplus_p$)

$$\forall e, e' \; e \oplus_p e' \leftrightarrow e \oplus_f e' \neq \perp (Definition)$$
$$\forall e \; e \oplus_p e (Reflexivity)$$
$$\forall e, e' \; e \oplus_p e' \rightarrow e' \oplus_p e (Symmetry)$$
$$\forall e, e', e'' e' \supset\!\subset e \wedge e'' \supset\!\subset e \rightarrow e' \oplus_p e'' \wedge e' \oplus_f e'' \supset\!\subset e (LeftAbut)$$
$$\forall e, e', e'' e \supset\!\subset e' \wedge e'' \oplus_p e \wedge e'' \oplus_p e' \rightarrow$$
$$\forall e''' (e''' \supset\!\subset e' \rightarrow e''' \oplus_p e \wedge (e \oplus_f e'') \oplus_f e'' \neq \perp)(LeftAbut\&Overlap)$$

For better understanding, the last two axioms are graphically depicted in: Figure 2

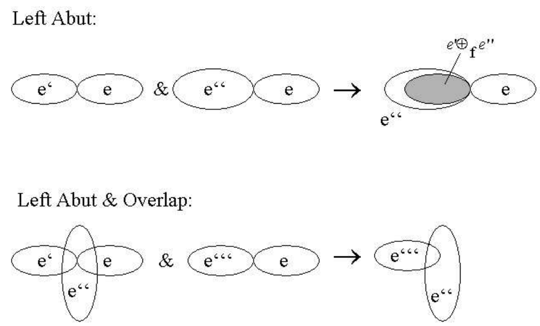

Fig. 2. Graphic representation of **Left Abut** and **Left Abut & Overlap**

Definition 4.9 (Imperfect)

$$\forall e\ eventuality(e) \wedge past(e) \wedge prog(e) \rightarrow (\forall e'(eventuality(e') \wedge past(e') \wedge e' \prec e \wedge \neg\exists(e'')(eventuality(e'') \wedge past(e'') \wedge perfect(e'') \wedge e' \prec e'' \prec e) \rightarrow e' \oplus_p e)$$

Further, we will have a homogeneity axiom similar to the one proposed in [1] stating that if a condition P holds at the eventuality e, then it also holds for any part of e. The way in which we express this is by saying that for any overlapping eventuality e' the conditions of e hold in particular at the intersection of e and e'. The following axiom is actually an axiom schema which needs to be instantiated for all different conditions which can hold at a given eventuality:

Definition 4.10 (Homogeneity)

$$\forall e, e'\ e \oplus_p e' \wedge P(e) \rightarrow P(e \oplus_f e')$$
$$\forall e, e'\ e \oplus_p e' \wedge \neg P(e) \rightarrow \neg P(e \oplus_f e')$$

Further, for events in general we assume the existence of an *event nucleus* structure as in [15] consisting of a preparatory and a consequent phase.

Definition 4.11 (Nucleus)

$$\forall e, e'\ e' \in prep(e) \rightarrow e' \in nucleus(e) \wedge e' \supset\subset e (Preparation)$$
$$\forall e, e'\ e' \in conseq(e) \rightarrow e' \in nucleus(e) \wedge e \supset\subset e' (Consequent)$$
$$\forall e, e', e''\ e'' \oplus_p e \wedge e' \in nucleus(e) \rightarrow e'' \oplus_p e' (NucleusOverlap)$$

4.5 World Knowledge

The last ingredient in our logical theory are axioms encoding world knowledge. Besides having axioms encoding a concept hierarchy with the corresponding disjointness axioms as described in [7], most importantly we will have axioms describing preconditions and effects of events. The axioms needed for the purposes of this paper are shown in Figure 3. It is important to note that most of the above axioms should actually be formulated in a non-monotonic

Definition 4.12 (Rooms have lamps; chandeliers are some sort of lamps)
$\forall r\ (room(r) \rightarrow \exists l\ lamp(l) \wedge in(l,r))\ \forall c\ (chandelier(x) \rightarrow lamp(c))$

Definition 4.13 (Entering a room)
$\forall e,p,r\ (enter(e) \wedge agent(e,p) \wedge patient(e,p) \wedge person(p) \wedge room(r) \rightarrow$
$\exists e',e''(e' \supset\subset e \wedge \neg loc(e',p,r) \wedge loc(e'',p,r) \wedge cause(e,e'') \wedge e \supset\subset e''))$

Definition 4.14 (Leaving a room)
$\forall e,p,r\ (leave(e) \wedge agent(e,p) \wedge patient(e,r) \wedge person(p) \wedge room(r) \rightarrow$
$\exists e',e''(e' \supset\subset e \wedge loc(e',p,r) \wedge \neg loc(e'',p,r) \wedge cause(e,e'') \wedge e \supset\subset e''))$

Definition 4.15 (Seeing implies same location)
$\forall e,p,o\ (see(e) \wedge agent(e,p) \wedge patient(e,o) \wedge person(p) \wedge object(o) \rightarrow$
$\exists l\ (loc(e,p,l) \wedge loc(e,o,l)))$

Definition 4.16 (Seeing through a windows implies a different location)
$\forall e,p,o\ (seeThroughWindow(e) \wedge agent(e,p) \wedge patient(e,o) \wedge person(p) \wedge object(o) \rightarrow$
$\exists l,l'\ (loc(e,p,l) \wedge loc(e,o,l') \wedge l \neq l'))$

An arrival always implies a preparatory traveling event as well as a means of transport spatio-temporally correlated with the traveler:

Definition 4.17 (Arriving implies travelling)
$\forall e,p,l\ arrive\_at(e,p,l) \wedge event(e) \wedge person(p) \wedge location(l) \rightarrow$
$\exists e' \wedge travel\_to(e',p,l) \wedge e' \in prep(e)$

Definition 4.18 (Travelling implies a mode of transport)
$\forall e,p,l\ travel\_to(e,p,l) \wedge event(e) \wedge person(p) \wedge location(l) \rightarrow$
$\exists m\ modeOfTransport(m) \wedge \exists l'(loc(e,p,l') \wedge loc(e,m,l'))$

Definition 4.19 (*loc* is functional) $\forall e,o,l,l'\ loc(e,o,l) \wedge loc(e,o,l') \rightarrow l = l'$

Definition 4.20 (Location)
$\forall o,l\ in(o,l) \rightarrow \forall e\ loc(e,o,l)$
$\forall e,o,o',l\ under(e,o,o') \wedge loc(e,o',l) \rightarrow loc(e,o,l)$
(...)

Fig. 3. World Knowledge Axioms

fashion, i.e. *it is only normally the case that if we see something through a window, the object in question is in another room.* However, a non-monotonic knowledge representation and reasoning scheme is not the focus of this paper, so that we gloss over aspects related to nonmonotinicity. The interested reader is referred to [14].

5 Application to Examples

Let's start the discussion of example 1.1. We will assume the input description 1 and get the following inferences:

1. $dconnected(e,e')$ (Event Connectedness)
2. $drel(e,e',narration) \vee ... \vee drel(e,e',result)$ (Discourse Relations)
3. $\exists l\ lamp(l) \wedge in(l,r)$ (Rooms have lamps) and $\forall e\ loc(e,l,r)$ (Location)
4. $\exists s,s'\ \neg loc(s,j,r) \wedge s \supset\subset e \wedge loc(s',j,r) \wedge e \supset\subset s' \wedge cause(e,s')$ (Entering)
5. $\exists l'\ location(l') \wedge loc(e',j,l') \wedge loc(e',c,l')$ (Seeing implies same location)
6. l=c (minimality)

Now interesting is how the computation of discourse relations is affected by the bridging reference resolution: Assume that e and e' are connected by *Narration*; then we get by **Temporal Consequences on Narration** as well as **Spatial Consequences on Narration**: $e < e'$ and $\exists l\ loc(s',j,l) \wedge loc(e',j,l)$. Assume that e and e' are connected by *Result*; then we get with **Consequences on Result**: $e \supset\subset e' \wedge cause(e,e')$ and thus $s' \oplus_p e'$ (**Left Abut**),

i.e. John's being in the room overlaps with the seeing.
Assume that e and e' are connected by *Explanation*; then we get with **Consequences on Explanation**: $e' \supset\!\subset e \wedge cause(e', e)$ and thus $s \oplus_p e'$ (**Left Abut**), the latter leading to a contradiction as s and e' have contradictory conditions. In fact, it holds that $\neg loc(s \oplus_f e', j, r)$ (from 4 above and **Homogeneity**) as well as $loc(s \oplus_f e', j, r)$ (from 3, 5 and 6 above, loc **is functional** and **Homogeneity**), which clearly results in a contradiction due to the fact that loc is functional. Thus, assuming that the chandelier is interpreted as belonging to the room, *Explanation* can not be inferred as discourse relation while *Result* and *Narration* are consistent with the assumption that the chandelier belongs to the room mentioned in the first sentence.

Given these explanations, examples 1.2 and 1.3 are easy to explain. In example 1.2, world knowledge implies that neither *Result* nor *Narration* can be inferred because in both cases a state s in which the condition $loc(s, j, r)$ holds would yield a contradiction with **seeing through a window implies different locations**. 'Leave' basically inverts the conditions of 'enter' such that we yield a similar contradiction as above when inferring *Result*. Inferring *Narration* does also yield a contradiction due to the spatial consequences on narration. In fact, the discourse relations *Result* or *Narration* can only be predicted in examples 1.2 and 1.3 if the chandelier is accommodated with the result that the model would not be minimal anymore.
For example 1.5, we assume the following input:

$$\exists e, e', j, o, c, p \; arrive\_at(e) \wedge agent(e, j) \wedge patient(e, o) \wedge$$
$$event(e) \wedge past(e) \wedge perfect(e) \wedge oasis(o) \wedge camels(c) \wedge$$
$$under(e', c, p) \wedge state(e') \wedge past(e') \wedge prog(e) \wedge palms(p)$$

Assuming that the palms are resolved as belonging to the oasis, we yield the following inferences:

1. $loc(e', p, o)$ and thus $loc(e', c, o)$ (Location)
2. $dconnected(e, e')$ (Event Connectedness)
3. $drel(e, e', narration) \vee ... \vee drel(e, e', result)$ (Discourse Relations)
4. $\exists e'' \; travel\_to(e'', j, o) \wedge e'' \in prep(e) \wedge e'' \supset\!\subset e$ (Arriving implies traveling & Prep)
5. $e' \oplus_p e$ (Imperfect) and thus $e' \oplus_p e''$ (Nucleus)
6. $\exists m \; modeOfTransport(m) \wedge loc(e'', j, l) \wedge loc(e'', m, l)$ (Mode of Transport)
7. $\neg loc(s, j, o) \wedge s \supset\!\subset e \wedge loc(s', j, o) \wedge e \supset\!\subset s'$ (Arrival)
8. $m = c$ (Minimality)

Thus we get an inconsistency in every model which identifies the camels c with the mode of transport m. This inconsistency is due to the fact that John is spatio-temporally correlated with the mode of transport during $(e'' \oplus_f s) \oplus_f e'$, i.e $loc((e'' \oplus_f s) \oplus_f e', j, l) \wedge loc((e'' \oplus_f s) \oplus_f e', c, l)$ (5,6 above, **Homogeneity**, **Left Abut**, **Left & Overlap**), which yields yield a contradiction with $\neg loc((e'' \oplus_f s) \oplus e', j, o)$ and $loc((e'' \oplus_f s) \oplus e', c, o)$ due to 1,7 above, **Homogeneity**, **Left Abut**, **Left Abut & Overlap** and **Loc is functional**.

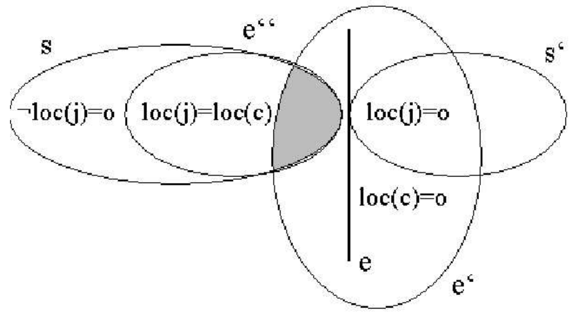

Fig. 4. Graphic representation of example 1.5.

6 Conclusion

We have presented an approach to bridging reference resolution taking into account the information flow between a certain resolution, the computation of discourse relations as well as linguistic and world knowledge. In our approach this information flow is declarative and emerges as a byproduct of building a minimal model for a logical theory as in [9]. Future work will clarify if off-the-shelf first-order model builders such as MACE or PARADOX can be used to implement this approach.

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