Model Generation in a Dynamic Environment*

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Abstract. Conventionally anaphora is seen as triggered by grammar, i.e. as a saturation requirement. In this paper, it is demonstrated how this assumption complicates anaphora resolution considerably and instead it is proposed to let the fly out of the bottle and reconsider grammar's contribution to anaphora resolution.

1 Introduction

Conventional anaphora resolution techniques rely on indication of anaphoric expressions. On some designs, anaphoric expressions introduce unresolved equations [9] or special predicates [1], while on others they are structurally different from resolved expressions [4,14]. Our point of departure is the observation that this kind of positive indication of anaphora is in fact redundant in most inference-based abductive or dynamic environments. This redundancy is demonstrated in Baumgartner and Kühn's (B&K) system [1], and indirectly in Bos' system [4] too. The important machinery in such systems is domain minimal model search. The domain minimal model is the model in which the most variables are assigned to the same individuals. Consequently, resolution comes for free if the assignments are properly restricted. This is the intuition behind our approach.

The next observation is standard in the literature: Antecedents must be appropriate and accessible [9-11]. Appropriateness is secured by the generation of consistent models, while accessibility must be ensured from other principles. In Kamp (1981), accessibility constraints are defined on the intermediate language of discourse representation structures and with respect to embedding. Our system is simpler in that no intermediate language is hypothesized. Accessibility is ensured by dynamic model generation, i.e. local inferences on logical forms.

Our approach is not just an improvement of B&K (1999), it is an extension. Introduction of discourse referents and accessibility constraints are ignored in their paper. In this respect, our approach is reminiscent of work in discourse representation theory (DRT) [4,9,11,14], but no unselective binding is introduced, so the proportion problem is avoided. Objections to DRT raised in Fodor and Sag (1982) are also met, since ambiguous indefinites are easily implemented.

A small HPSG fragment and a model generator is defined. The output of the grammar is used to generate first order models, and the accessibility conditions

* Thanks to the two anonymous reviewers for their helpful comments.

are directly implemented in the knowledge base of the model generator. The output model is added to this base in the update algorithm's last step.

2 Positive Constraints on Coreference

B&K discuss the somewhat odd example in (1). Their intuition is that *the criminal* refers to the gangster, by default. The resolution results from their definition of abductive explanation, their notion of (predicate-specific) minimality – which simply says that the minimal model we are interested in, is the one with the least number of instances of **anaphor**-predicates – and the semantics of anaphoric expressions.

(1) *a.* A politician chased a gangster. *b.* The criminal died.

Definition 1 (Abductive explanation). *Ω is the set of observations, Σ the background theory and Δ the abducibles. Γ is an abductive explanation iff: $\Gamma \subseteq \Delta$, $\Sigma \cup \Gamma \models \Omega$ and $\Sigma \cup \Gamma$ is satisfiable.*

(1a) adds the following to Σ, which already contains the implication that gangsters are criminals: $\mathbf{politician}(c_1) \wedge \mathbf{gangster}(c_2) \wedge \mathbf{chase}(c_1, c_2)$. B&K offer no explanation of how indefinites introduce discourse referents; this issue is addressed below. In terms of abductive reasoning, the observation that has to be explained in (1b), is that one of the discourse referents is a (dying) criminal, i.e. $\Omega = \exists x_1.\mathbf{anaphor}_1(x_1) \wedge \mathbf{criminal}(x_1) \wedge \mathbf{die}(x_1)$. The abducibles Δ are $\{\mathbf{anaphor}_1(c_1), \mathbf{anaphor}_1(c_2)\}$.[1] Since the abductive explanation must be a subset of Δ according to Definition 1, there are four candidates for such explanations: $\Gamma_1 = \{\}$, $\Gamma_3 = \{\mathbf{anaphor}_1(c_2)\}$, $\Gamma_2 = \{\mathbf{anaphor}_1(c_1)\}$ and $\Gamma_4 = \{\mathbf{anaphor}_1(c_1), \mathbf{anaphor}_1(c_2)\}$. Γ_1 is in conflict with Definition 1, and more specifically, with $\Sigma \cup \Gamma \models \Omega$. Γ_2 and Γ_3 are both possible solutions. Γ_4 is a bad explanation, since it is not $\mathbf{anaphor}_1$-minimal. B&K argue that "Γ_2 is excluded, since it does not entail with Σ the last part of the observation Ω, namely $\exists x_1.\mathbf{criminal}(x_1)$." It is not clear to me what they mean, but Γ_2 can be excluded on different grounds under local minimality (Definition 2 at page 3).

politician(c_1)
gangster(c_2)
chase(c_1, c_2)
criminal(c_2)

$\mathbf{anaphor}_1(c_1)$	$\mathbf{anaphor}_1(c_2)$
$\mathbf{criminal}(c_1)$	$\mathbf{die}(c_2)$
$\mathbf{die}(c_1)$	

Some Empirical Inadequacies. In addition to the revision of the definition of model minimality, certain other revisions are necessary to make this framework empirically adequate. B&K let definite noun phrases introduce anaphoric relations (presumably excluding generics, e.g. *la vecchiaia*, 'old age', and noun

[1] B&K write the abducibles in this way, but the **anaphor**-predicates abbreviate formulae, it seems, e.g. $\mathbf{anaphor}_1(c_i) \wedge \mathbf{criminal}(c_i) \wedge \mathbf{die}(c_i)$. Otherwise $\Sigma \cup \Gamma \not\models \Omega$.

phrases denoting unique entities, e.g. *il sole*, 'the sun'), but this is not a viable solution in general, since definite noun phrases sometimes introduce new discourse referents. In certain contexts, the definite noun phrase may be said to refer to an implicit discourse referent, as in (2), but this approach will run into problems when trying to explain examples such as (3,4):

(2) C'è un negozio, è la commessa ... ('there is a store, and the salesgirl ... ')
(3) Ho perso l'orologio. ('I've lost my (the) watch')
(4) La signora Anna Maria è una bella donna dai capelli rossi e dai molti gioielli. ('AM is a beautiful lady with (the) red hair and (the) many jewels')

If the definite noun phrases in (3,4) were anaphoric expressions, the existence of a person would somehow imply the existence of watches, red hair and jewels. This is nonsensical. Only in designs with strong accommodation mechanisms (e.g. [14]) can definites be uniformly assigned anaphoric relations.

Inefficiencies. B&K employ predicate-specific minimality. If they had employed the more standard notion of local minimality, they would have been able to simplify their account considerably, since the unification of variables then comes for free. This objection also addresses new and classical DRT [10]. Consider the derivation of (1) and assume local minimality. It is now possible to ignore the abducibles. Consequently, three assignments of the variable in Ω are available:

$$\begin{array}{c}
\mathbf{politician}(c_1) \\
\mathbf{gangster}(c_2) \\
\mathbf{chase}(c_1, c_2) \\
\mathbf{criminal}(c_2) \\
\begin{array}{c|c|c}
\mathbf{criminal}(c_1) & \mathbf{die}(c_2) & \mathbf{criminal}(c_3) \\
\mathbf{die}(c_1) & & \mathbf{die}(c_3)
\end{array}
\end{array}$$

It is evident that the assignment $g(x_1) = c_2$ is the locally minimal explanation. It results in fewer relations than $g(x_1) = c_1$ and fewer individuals than $g(x_1) = c_3$. The notion of local minimality is formally defined below. In addition, B&K must also address the issue of referent-introduction. How do they analyze indefinites? On their account, nothing ensures the indefinite is not coreferential with an antecedent referential expression. Finally, B&K introduce no straightforward way of implementing accessibility constraints.

3 Preliminaries on Model Generation

Various notions of model minimality are proposed in the literature [11], but *local minimality* seems to be of interest in the context of anaphora resolution. A model is an interpretation of some utterance u, say (4), iff it satisfies $\Sigma \cup \Gamma_u$. The preferred interpretation is the locally minimal model, and the set of theories is the Cartesian product of $\{\Sigma\}$ and the set of explanations.

Definition 2 (Local minimality). *Say two theories Θ_i and Θ_j are satisfied by $\mathfrak{M}_i$ and $\mathfrak{M}_j$. $\mathfrak{M}_i$ is the locally minimal model only if $|\mathfrak{M}_i|_\iota \leq |\mathfrak{M}_j|_\iota$ (where $|.|_\iota$*

assigns cardinality to structures) and vice versa. If $|\mathfrak{M}_i|_\iota = |\mathfrak{M}_j|_\iota$*, then* $\mathfrak{M}_i$ *is the minimal model if* $|\mathfrak{M}_i|_\rho \leq |\mathfrak{M}_j|_\rho$ *(*$|.|_\rho$ *is a function that outputs the number of relations in a structure) and vice versa. The binary relation symbol* $\preceq$ *denotes local minimality, i.e. if* $\mathfrak{M}_i$ *is more locally minimal than* $\mathfrak{M}_j$*,* $\mathfrak{M}_i \preceq \mathfrak{M}_j$*.*

Consider the interpretation of (1). $\Sigma_{(1a)}$ at the time (1a) is uttered, is different from $\Sigma_{(1b)}$ at the time (1b) is uttered, since (1a) updates $\Sigma_{(1a)}$. This temporal notion of update is used to define informativity.

Definition 3 (Informativity). *In* $\{u_i, u_j\}$*,* u_j *is informative, iff* $\mathfrak{M}_{u_i} \not\models u_j$*.*

An informativity constraint is added to our hypothesis about preferred interpretations:

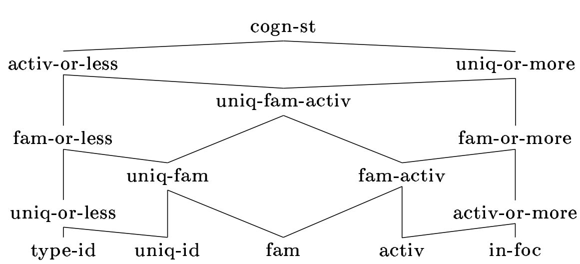
Definition 4 (Preferred interpretations). *The preferred interpretation of an utterance* u_j *in some discourse* $\{u_1, \ldots, u_i, u_j, \ldots, u_n\}$ *is* $\mathfrak{M}_{u_j}$ *such that:*$\mathfrak{M}_{u_j} \models u_j \cup \Sigma$*,*$\mathfrak{M}_{u_j} \preceq \mathfrak{M}'_{u_j}$ *for any model* $\mathfrak{M}'_{u_j}$ *such that* $\mathfrak{M}'_{u_j} \models u_j \cup \Sigma$*, and*$\mathfrak{M}_{u_i} \not\models u_j$*.*

The minimal model of (4), on this hypothesis, and relevant lexical semantics (ignoring givenness, which is introduced below, the internal complexity of the plural *molti gioielli*, and an adequate semantics of proper names), is $\mathfrak{M}_{(4)} = \{\mathbf{beautiful}(a), \mathbf{female}(a), \mathbf{poss}(a, c_1), \mathbf{hair}(c_1), \mathbf{red}(c_1), \mathbf{poss}(a, c_2), \mathbf{jewels}(c_2)\}$.

4 Negative Constraints on Coreference

Assume Definition 4. One complexity to our account is the restriction on indefinites that in most contexts they introduce discourse referents. This question is never addressed by B&K. The exact design of the mechanism depends on how determination or *givenness* is accounted for. The conventional encoding of givenness is by lexically introduced operators, e.g. the ι-operator. Instead a scalar set of givenness predicates with set-theoretic interpretations is introduced here. Compositionally, givenness is computed at the constructional level.

Givenness. The intuition behind constructional computation of givenness is that adnominals constrain givenness rather than introduce it. The values are given in the hierarchy below, inspired by Gundel et al. (1993). They are forced down the hierarchy, as you're chased up the syntactic tree, so to say.



The hierarchy is used to account for light pronouns and bare singulars [2], and declension, vocatives and discourse givenness [16]. The values are subtypes of the predicate value, so they can be directly employed in logical form. The logical form of (4) is then (ignoring tense and simplifying quantification): $\mathbf{type\_id}(a) \wedge \mathbf{beautiful}(a) \wedge \mathbf{female}(a) \wedge \exists x_1.\mathbf{poss}(a, x_1) \wedge \mathbf{uniq\_or\_more}(x_1) \wedge \mathbf{hair}(x_1) \wedge \mathbf{red}(x_1) \wedge \exists x_2.\mathbf{poss}(a, x_2) \wedge \mathbf{uniq\_or\_more}(x_2) \wedge \mathbf{jewels}(x_2)$. As should be obvious from this, $\lambda x_1.\mathbf{type\_id}(x_1)$ is the set of things given as types (in a non-technical sense), while $\lambda x_1.\mathbf{uniq\_or\_more}(x_1)$ is the set of things uniquely given. A subset of $\lambda x_1.\mathbf{uniq\_or\_more}(x_1)$ is e.g. the set of things in focus, which typically are referred to by pronouns. The important thing to note, however, is that, in restricted ways, objects can be referred to differently throughout a discourse. For instance, something given as a type in one utterance, may be given as a uniquely identified referent in the subsequent discourse, but not reversely.

A Constraint on Indefinites. Index givenness predicates (cf. **anaphor**-predicates in [1]). Translate the type hierarchy into a set of meaning postulates $\Pi \in \Sigma$. The constraint that indefinites introduce referents is formally stated in (A):

(A) $\neg\exists x_1.\mathbf{cogn\_st}_i(x_1) \wedge \mathbf{type\_id}_j(x_1)$ *where* $i < j$

Indefinites now introduce referents, since any individual is in $\lambda x_i.cogn\_st(x_i)$.

Example 5. Revisit (1). The logical form of the two utterances are, respectively, $\exists x_1.\exists x_2.\mathbf{type\_id}_1(x_1) \wedge \mathbf{politician}(x_1) \wedge \mathbf{type\_id}_1(x_2) \wedge \mathbf{gangster}(x_2) \wedge \mathbf{chase}(x_1, x_2)$ and $\exists x_1.\mathbf{uniq\_or\_more}_2(x_1) \wedge \mathbf{criminal}(x_1) \wedge \mathbf{die}(x_1)$. If Σ, soundly, conjoins $\neg\exists x_1.\mathbf{chase}(x_1, x_1)$ and $\forall x_1.\mathbf{gangster}(x_1) \rightarrow \mathbf{criminal}(x_1)$, a tableaux equivalent to the one on page 3 is derived. Compare this to (5):

(5) *a.* A politician chased a gangster. *b.* A criminal died.

$\mathbf{politician}(c_1)$
$\mathbf{type\_id}_1(c_1)$
$\mathbf{gangster}(c_2)$
$\mathbf{type\_id}_1(c_2)$
$\mathbf{chase}(c_1, c_2)$
$\mathbf{criminal}(c_2)$

$\mathbf{type\_id}_2(c_1)$	$\mathbf{type\_id}_2(c_2)$	$\mathbf{type\_id}_2(c_3)$
$\mathbf{criminal}(c_1)$	$\mathbf{die}(c_2)$	$\mathbf{criminal}(c_3)$
$\mathbf{die}(c_1)$	*	$\mathbf{die}(c_3)$
*		

Now two of the assignments are suddenly inconsistent. The preferred one corresponds to our intuitions about the discourse's meaning.

Objections. On the current design, all variables are unified as long as $\Sigma \cup \Gamma$ is satisfiable, i.e. the analysis is consistent with the knowledge base, and the resulting model is minimal and informative. However, there are additional constraints on coreference, which we have not accounted for. One of these is the problem of partial accessibility. In DRT, an antecedent should be both appropriate and accessible [9-11]. Appropriateness is ensured. Accessibility is restricted by levels of embedding in discourse representation structures. Can we do something similar on our design? The problem is quantificational noun phrases, (indefinites introduced in negative and conditional contexts automatically resist coreference, since they have no representation in locally minimal models).

The simple step to implement accessibility constraints on quantificational noun phrases is to introduce a quantifier hierarchy, similar to our givenness hierarchy. Such quantifier hierarchies are independently motivated in Søgaard and Haugereid (2005), e.g. it was used to explain restrictions of measure phrases, quantifier float and agreement in the prenominal field. A constraint (B) is now added to Σ. Of course the quantifier values of individuals must be constantly updated. The flexibility of our design allows us to implement the ambiguity between referential and quantificational uses of indefinites (important in negative and conditional contexts), observed by Fodor and Sag (1982).

(B) $\neg\exists x_1.\mathbf{quant\_np}_i(x_1) \wedge \mathbf{in\_foc}_j(x_1)$ *where* $i < j$

5 Fragment

In this section, a fragment is defined for small discourses like:

(6) *a.* A man$_i$ snores. *b.* The man$_i$ sleeps.
(7) *a.* *The man$_i$ snores. *b.* A man$_i$ sleeps.
(8) *a.* *All men$_i$ snore. *b.* The man$_i$ sleeps.

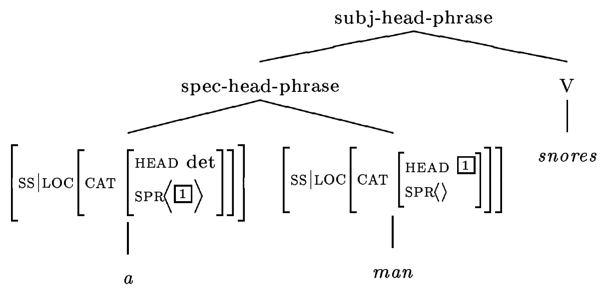
Lexicon. The lexical entries are relatively simple:

$$\begin{bmatrix} \text{PHON} \ \langle \text{a} \rangle \\ \text{SS|LOC} \begin{bmatrix} \text{CAT|HEAD det} \\ \text{CONT|HOOK|INDEX} \begin{bmatrix} \text{GIVENNESS type\_id} \\ \text{QUANT exists} \\ \text{NUMBER sg} \end{bmatrix} \end{bmatrix} \end{bmatrix} \begin{bmatrix} \text{PHON} \ \langle \text{all} \rangle \\ \text{SS|LOC} \begin{bmatrix} \text{CAT|HEAD quant} \\ \text{CONT|HOOK|INDEX} \begin{bmatrix} \text{GIVENNESS uniq\_id} \\ \text{QUANT forall} \\ \text{NUMBER pl} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

$$\begin{bmatrix} \text{PHON} \ \langle \text{man/men} \rangle \\ \text{SS|LOC} \begin{bmatrix} \text{CAT|HEAD noun} \\ \text{CONT|HOOK|INDEX} \begin{bmatrix} \text{GIVENNESS cogn\_st} \\ \text{QUANT quant\_min} \\ \text{NUMBER sg/pl} \end{bmatrix} \end{bmatrix} \end{bmatrix} \begin{bmatrix} \text{PHON} \ \langle \text{snores/snore} \rangle \\ \text{SS|LOC} \begin{bmatrix} \text{CAT|HEAD verb} \\ \text{CONT|HOOK|INDEX} \begin{bmatrix} \text{GIVENNESS cogn\_st} \\ \text{QUANT quant\_min} \\ \text{NUMBER sg/pl} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

$$\begin{bmatrix} \text{PHON} \ \langle \text{sleeps} \rangle \\ \text{SS|LOC} \begin{bmatrix} \text{CAT|HEAD verb} \\ \text{CONT|HOOK|INDEX} \begin{bmatrix} \text{GIVENNESS cogn\_st} \\ \text{QUANT quant\_min} \\ \text{NUMBER sg} \end{bmatrix} \end{bmatrix} \end{bmatrix} \begin{bmatrix} \text{PHON} \ \langle \text{the} \rangle \\ \text{SS|LOC} \begin{bmatrix} \text{CAT|HEAD det} \\ \text{CONT|HOOK|INDEX} \begin{bmatrix} \text{GIVENNESS uniq\_id} \\ \text{QUANT quant\_min} \\ \text{NUMBER sg-pl} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Grammar. Assume a Head Specifier Rule [13] and Minimal Recursion Semantics [5-6]. Then (6a) is parsed as:



The *head-subj-phrase* inserts the quantifier, but selects the quantificational value from the index of the subject (i.e. the indices of its daughters).

$$\begin{bmatrix} \textit{head-subj-phrase} & \\ \text{C-CONT} & \begin{bmatrix} \text{RELS} & \left\langle \begin{bmatrix} \textit{quant-rel} \\ \text{LBL } \boxed{0} \\ \text{PRED } \boxed{1} \\ \text{ARG0 } \boxed{2} \begin{bmatrix} \text{QUANT } \boxed{1} \end{bmatrix} \\ \text{RESTR } \boxed{3} \end{bmatrix} \right\rangle \\ \text{HCONS} & \left\langle \begin{bmatrix} \text{HARG } \boxed{3} \\ \text{LARG } \boxed{4} \end{bmatrix} \right\rangle \end{bmatrix} \\ \text{N-H-DTR} & \begin{bmatrix} \text{SS}|\text{LOC}|\text{CONT}|\text{HOOK} & \begin{bmatrix} \text{LTOP } \boxed{4} \\ \text{INDEX } \boxed{2} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Similarly, a givenness predicate is inserted at this level. Consequently, the scoped *mrs*s of (6a) and (6b) are $\exists x_1.\mathbf{man}(x_1) \wedge \mathbf{type\_id_1}(x_1) \wedge \mathbf{snore}(x_1)$ and $\exists x_2.\mathbf{man}(x_2) \wedge \mathbf{uniq\_id_2}(x_2) \wedge \mathbf{sleep}(x_2)$. In Σ, nothing prevents that $g(x_1) = g(x_2)$. Consequently, the locally minimal model satisfying (6) contains one individual, i.e. anaphora resolution is performed. Consider the output for (7): $\exists x_1.\mathbf{man}(x_1) \wedge \mathbf{uniq\_id_1}(x_1) \wedge \mathbf{snore}(x_1)$ and $\exists x_2.\mathbf{man}(x_2) \wedge \mathbf{type\_id_2}(x_2) \wedge \mathbf{sleep}(x_2)$. In this case, $g(x_1) \neq g(x_2)$, since (A) ensures that $\neg\exists x_1.\mathbf{uniq\_id}_1(x_1) \wedge \mathbf{type\_id}_2(x_1)$. This is why coreference fails in (7). This effect is ensured in (8) by number agreement, while (B) ensures it for discourses like:

(9) *a.* Each man$_i$ snores. *b.* The man$_i$ sleeps.

Grammar and Inference. Satisfiability, local minimality and informatitivity are general pragmatic constraints on discourse interpretation. Grammar encodes the constraints a constituent puts on agreement, etc., but says nothing about which elements are likely to be coreferential. Compared to Bos (2003b), no account was given for presuppositional effects. It is rather predicted that presuppositional effects are extragrammatical, and that the oddness it causes to violate presuppositions is only pragmatic of nature. E.g. if (9b) is parsed in isolation, our algorithm still produces a model $\mathfrak{M}_i : \{\mathbf{man}(c_1), \mathbf{uniq\_id}(c_1), \mathbf{sleep}(c_1)\}$. If the utterance is considered odd, this is only a result of pragmatics. In our view, pragmatics should be modelled independently.

6 Conclusion

The fragment is a small grammar that outputs scoped *mrs*s, which are forwarded to the inference module. The inference module is used to derive the preferred interpretation (cf. Definition 4). On related implementations, see e.g. [3,11,15]. The system introduces no intermediate structures, but consists only of a grammar and an inference module (that includes a knowledge base). Computationally, the flow is from the parser to, say, a theorem prover and a model generator. The only complication is to extract relevant information from the computed models to the knowledge base; for details, see [15]. This last step is the update function.

In processing, the system generates global models to resolve anaphora, ambiguities, etc. Bos (2003b) speculates that more efficient algorithms may exploit some form of incremental model generation. It may also be useful to distinguish between local and global questions, i.e. anaphora may be resolved by local model generation. This issue is left for further research.

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