Verifying binding constraints for anaphor resolution

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Proceedings of the 12th International Conference on
Head-Driven Phrase Structure Grammar

Department of Informatics, University of Lisbon

Stefan Müller (Editor)

2005

Stanford, CA: CSLI Publications

pages 614–634

Stuckardt, Roland. 2005. Verifying binding constraints for anaphor resolution. In Stefan Müller (ed.), *Proceedings of the 12th International Conference on Head-Driven Phrase Structure Grammar, Department of Informatics, University of Lisbon*, 614–634. Stanford, CA: CSLI Publications. DOI: 10.21248/hpsg.2005.35.


Abstract

Algorithmic approaches to anaphor resolution are known to benefit substantially from syntactic disjoint reference filters. Typically, however, there is a considerable gap between the scope of the formal model of grammar employed for deriving referential evidence and its implementation. While accounting for many subtleties of language, such formal models at most partially address the algorithmic aspects of referential processing. This paper investigates the issue of implementing syntactic disjoint reference for robust anaphor resolution. An algorithmic account of binding condition verification will be developed that, on one hand, captures the theoretical subtleties, and, on the other hand, exhibits computational efficiency and fulfils the robustness requirements. Taking as input the potentially fragmentary parses of a robust state-of-the-art parser, the practical performance of this algorithm will be evaluated with respect to the task of anaphor resolution and shown to be nearly optimal.

1 Introduction

Syntactic disjoint reference rules are known to be of paramount importance to robust, algorithmic[1] anaphor resolution. Starting with the pioneering paper of Hobbs (1978), a plethora of algorithms has been developed that exploits this source of evidence as a filter for narrowing down sets of antecedent candidates for anaphoric expressions. Among this work are the landmark approach of Lappin and Leass (1994) and its numerous robust, knowledge-poor descendants, e. g. Kennedy and Boguraev (1996); Mitkov (1998); Stuckardt (2001). These approaches employ syntactic disjoint reference rules that capture referential evidence derived from formal models of grammar such as Government and Binding (GB) Theory (Chomsky (1981)) to the extent that it is deemed relevant to accomplish the task of anaphor resolution.

In general, there is a considerable gap between the scope of the formal model and its algorithmic implementation. In dealing with issues well beyond anaphora and in claiming cross-linguistic generality, GB theory refers to complex descriptions of syntactic surface structure that, today as well as in the near future, no robust parser can be expected to construct automatically. Thus, while accounting for many subtleties of language, such formal models at most partially address the *algorithmic* aspects of referential processing that are relevant for practical tasks of referential disambiguation.

Nevertheless, robust anaphor resolution approaches require implementations of syntactic disjoint reference that gather as much evidence as possible. This paper investigates the issue of implementing syntactic disjoint reference for robust anaphor resolution. An algorithmic account of binding condition (BC) verification will be

[1] The adjectives *robust* and *algorithmic* are conceived as synonyms here. Henceforth, they are employed interchangeably for qualifying approaches to anaphor resolution that are fully implemented and work without human intervention. Equally well one might speak of *operational* or *practical* anaphor resolution.

developed that, on one hand, captures the theoretical subtleties, and, on the other hand, exhibits computational efficiency and fulfils the robustness requirements.

The paper is organized as follows. Section 2 recapitulates the formal notions of Chomsky's GB theory to the extent relevant to the subsequent discussion. In particular, a number of central issues regarding the GB predictions on coreference are identified that, while being important for accomplishing the task of anaphor resolution, are neglected by many algorithmic accounts of binding. In section 3, starting with an identification of the scope of Chomsky's original algorithm for determining admissible index assignments, different algorithmic approaches to binding condition verification are put under scrutiny. Limitations are identified that render these approaches insufficient. In section 4, departing from a closer analysis of the robustness requirements in the context of state-of-the-art parsers that yield fragmentary output, an algorithmic account of binding is developed that fulfils the theoretical and practical requirements and that can thus be employed as part of a robust rule-based anaphor resolution algorithm. An implementation and evaluation with respect to the task of robust anaphor resolution on fragmentary parses gives evidence that the binding condition verification algorithm performs nearly optimal.

2 A Formal Model of Syntactic Disjoint Reference

2.1 GB Theory

By referring to the Government and Binding Theory of Chomsky, the core of the syntactic coindexing restrictions may be stated as follows (Chomsky (1981)):[2]

Definition
Binding Principles A, B, and C:[3]

(A) A reflexive or reciprocal is bound in its binding category.

(B) A pronoun is free (i.e. not bound) in its binding category.

(C) A referring expression[4] is free in any domain.

where **binding category** denotes the next surface-structural dominator containing some kind of subject, and **binding** is defined as *coindexed and c-commanding*:

Definition
Surface structure node X **c-commands** node Y if and only if the next branching node which dominates X also dominates Y and it is not the case that X dominates Y, Y dominates X, or X = Y.

[2]Various theoretical models that cover disjoint reference phenomena have been stated. Since the disjoint reference conditions are descriptive principles of grammar, the choice of the theoretical model is, in this sense, arbitrary. In the subsequent discussion, the comprehensive and widely known GB theory is explicated. Equally well one might refer to the approach to binding theory proposed by Pollard and Sag (1994).

[3]For languages such as Portuguese, a fourth binding principle (*Z*, not covered by original BT) might be distinguished, which accounts for cases of *long-distance reflexives*.

[4]e.g. common nouns and names

Some examples which illustrate the scope of the binding principles are

(1a) *The barber$_i$ is shaving himself$_i$ / $*$him$_i$.*
(1b) *The client$_i$ wants that the barber$_j$ shaves $*$himself$_i$ / him$_i$.*
(1c) *$*$ The client$_i$ wants that the barber$_j$ shaves the client$_i$.*

In sentence *(1a)*, whereas the reflexive *himself* is required to be coindexed with the local subject *the barber* (BP A), coindexing the pronoun *him* with the subject is ruled out (BP B) because, otherwise, the pronoun would be locally bound in its binding category. Sentence *(1b)* illustrates the case of non-local binding (here: outside the embedded sentence) which is admissible only for the non-reflexive pronoun. As illustrated by sentence *(1c)* and modeled by BP C, referring expressions (e.g. common nouns and names) are not even allowed to be bound non-locally.

A further structural well-formedness restriction, commonly named **i-within-i condition**, aims at ruling out certain instances of referential circularity, i.e. coindexings matching the pattern $[\alpha \ \ldots \ [\beta \ \ldots \ ]_i]_i$ (Chomsky, 1981, page 212). It is motivated by cases like

(2) *$*$ Mary knows [the owner of his$_i$ boat]$_i$.*

2.2 GB predictions for anaphora processing: a closer look

In order to adequately operationalize the binding conditions for the task of anaphora processing, the implementation has to take into account some subtleties that are not adequately captured by algorithms described in previous work.

2.2.1 Taking into account the binding condition of the antecedent

Considering the issue of binding from the perspective of the algorithmical task of anaphor resolution, which is typically conceived as the problem of determining admissible antecedent candidates for anaphors, one might be tempted to interpret the predictions of binding theory *asymetrically*. Regarding nonreflexive pronouns, for instance, antecedent candidates are sought for that do not locally bind the pronoun, for which BP B applies. However, since coindexing is a symmetrical relation, one has to take into account the BP of the antecedent candidate as well. E. g., in

(3) *$*$ He$_i$ is shaving the client$_i$.*

while the binding constraint of *he* is satisfied, coindexing this pronoun with the NP *the client* (which might be conceived as antecedent candidate during anaphor resolution) is nevertheless inadmissible as BP C of the NP would be violated.[5]

[5]This elementary example, which shows an instance of backward anaphora, has been choosen for reason of expository simplicity. There are as well cases of forward anaphora in which this issue is important.

2.2.2 Accounting for decision interdependency

More importantly, however, but nevertheless not covered by many algorithmic approaches to binding, the *transitivity* of the coindexing relation should be taken into account. Here, the misconception consists in identifying the task of determining admissable index assignments with the task of determining sets of (isolated) pairs (α, γ) of anaphors α and antecedents γ to be coindexed. However, as illustrated by the following example, this falls short of avoiding transitive violations of the binding constraints:

(4) $*$ *The architect*$_i$ *promises that he*$_i$ *is going to support him*$_i$.

While, *individually*, it is admissible to coindex the type C NP *The architect* with either of the type B pronouns *he* and *him*, taken together, these anaphor resolution decisions violate the binding condition of *him* as it becomes transitively coindexed with the locally c-commanding occurrence *he*.[6]

2.2.3 Strong vs. weak application of BP A

While it is important to take into account the binding conditions of anaphor *and* antecedent candidate and to provide a mechanism for avoiding mutually incompatible individual decisions (α, γ), care should be taken not to over-interpret the requirements for reflexive and reciprocal pronouns, as the applicable BP A merely demands the existence of *one* locally c-commanding binder, but doesn't preclude the existence of further coindexed occurrences, as illustrated by

(5) *The barber*$_i$ *admits that he*$_i$ *shaves himself*$_i$.

This *weak* (henceforth also called *non-constructive*) interpretation of BP A should be applied whenever checking for decision interdependency or when considering type A pronouns as antecedent candidates. This will become more clear in section 4.4 where the algorithmic verification of the binding conditions is integrated into a robust anaphor resolution algorithm.

2.2.4 Non-finite local domains of binding

Binding categories are not exclusively contributed by finite clauses. There are other syntactic configurations that match the definition given in section 2.1. In particular, the various types of possessive markers, such as possessive pronouns, are considered to constitute *logical subjects* in the sense of the GB theory, thus inducing local domains as well. The following examples illustrate that, if one thus considers NPs modified by a possessor as binding categories, binding principles A and B yield the right predictions, as the NP-local binding of reflexive pronouns is enforced, and the NP-local binding of non-reflexive pronouns is ruled out:

[6] Cases of decision interdependency can even be the consequence of choosing an identical *inter*sentential antecedent for pronouns occurring in the same local domain of binding. In this sense, the predictions of BT might have repercussions for instances of intersentential anaphora.

(6a) *The barber$_i$ hears [Peter's$_j$ story about himself$_j$].*
(6b) $*$ *The barber$_i$ hears [Peter's$_j$ story about himself$_i$].*
(6c) $*$ *The barber$_i$ hears [Peter's$_j$ story about him$_j$].*
(6d) *The barber$_i$ hears [Peter's$_j$ story about him$_i$].*

Hence, an appropriate implementation of the binding condition verification should cover these - and other -[7] cases, as well.

2.2.5 Empty categories

An even more intricate, but (as will become evident during the subsequent discussion) technically related issue is the proper treatment of *empty categories*, which are known to play a central role for the modeling of binding phenomena in GB theory. Empty categories might be characterized as *implicit* occurrences (index bearers), i. e. surface-structural entities for which no immediate counterpart at the level of linguistic expressions exist. Corresponding to the different ways of binding-theoretical treatment, several types of empty categories are distinguished.

Traces are employed for modeling instances of transformation (Move-α) in the theoretical mapping process between deep structure and surface structure. Traces *t* are introduced at the origin (and, possibly, intermediate positions) of the moved element and taken to be coindexed with it. The following examples illustrate that binding theory yields the right predictions given that, as stated by GB theory, "*Wh*" traces are assumed to be subject to binding principle B:

(7a) *[Who$_i$] does his$_i$ mother love $\underline{t_i}$?*
(7b) $*$ *[Who$_i$] does he$_i$ love $\underline{t_i}$?*
(7c) *[Which picture of himself$_j$]$_i$ does John$_j$ like t_i?*

Whereas, in case *(7a)*, the trace *t* might be coindexed with the possessive *his$_i$*, which constitutes a non-finite local domain of binding, in case *(7b)*, the coindexing of *t* with the subject *he$_i$* of the embedded clause is ruled out as the latter would locally bind the former, thus violating BP B. Example *(7c)* illustrates an even more subtle case in which the sole admissible antecedent candidate of the reflexive pronoun *himself$_j$* is only available at the original position of the moved element. Thus, properly accounting for the binding condition verification of the trace representing the moved element does not suffice; further means are regarded to be necessary in order to adequately care for anaphoric entities *contained in* the moved element.

In GB theory, so-called **pro** elements constitute a second type of empty categories. They are used for surface-structurally modeling certain instances of implicit (unrealized) finite clause subjects, which are observed in languages such as Italian (*pro-drop languages*). *pro* denotes a formal substitute of the subject; if the entity implicitly referred to by the omitted subject is realized somewhere else in the sentence, the *pro* element serves as an expletive that is coindexed with the other occurrence(s). Some examples for Italian (cited from Giorgi et al. (1990)) are:

[7] E.g., in German, participles employed as adjectives (*Gerundiva*) might give rise to local domains of binding.

(8a) *pro$_i$ telefona. ("He/she [determined by context] is phoning.")*
(8b) *pro$_i$ telefona lui$_i$. ("He is phoning.")*
(8c) *Gianni$_i$ ha detto che pro$_j$ arriveà [la propria$_i$ madre]$_j$.*
"Gianni has said that his Mother will arrive."

Due to theoretical reasons, *pro* elements are interpreted to be subject to binding principle B as well (see Chomsky (1986), p. 164). However, as has been already pointed out by Giorgi et al. (1990), additional means have to be taken not to interpret the configurations in cases such as *(8b)* and *(8c)* as violations of the binding principle (B or C) of the implicit subject's postponed occurrence. Regarding binding condition verification, Giorgi et al. (1990) thus suggest that the local binding of the postponed subject through the respective *pro* element should be considered to be an admissible exempt case.

Whereas the coverage of *pro* elements might be considered to be of primarily theoretical importance, there is a third type of empty categories distinguished by GB theory the proper algorithmic treatment of which seems to be of higher practical relevance to anaphor resolution. The surface-structural model of certain types of infinitival complements is considered to contain so-called **PRO** elements, which, as above, represent formal substitutes for unrealized (implicit) subjects. These substitutes are required as the infinitival complement might contain further referential entities the anaphoric capabilities of which are determined by the index of the implicit entity. As illustrated by the following examples, depending upon the verb of the matrix clause (e.g., *promise* vs. *persuade*), the respective *PRO* element is considered to be coindexed either with the subject or the object of the matrix clause (*subject control* vs. *object control*); this determines the option for the referential interpretation of the type A pronoun, which requires a binder inside (local to) the infinitival complement:

(9a) *The barber$_i$ promises the client$_j$ PRO$_i$ to shave himself$_i$.*
(9b) $*$ *The barber$_i$ promises the client$_j$ PRO$_i$ to shave himself$_j$.*
(9c) $*$ *The barber$_i$ persuades the client$_j$ PRO$_j$ to shave himself$_i$.*
(9d) *The barber$_i$ persuades the client$_j$ PRO$_j$ to shave himself$_j$.*

The binding-theoretical type of the *PRO* occurrence (either A or B) is considered to depend upon further contextual criteria.[8] However, regardless of the theoretical intricacies concerning the property of the *PRO* element itself,[9] the important observation to be made here is that the binding condition verification of anaphoric expressions occurring inside infinitival complements might require additional efforts. An adequate implementation of binding condition verification should hence account for this issue.

Thus, at least from a theoretical point of view, the proper algorithmic coverage of empty categories seems to be important since, in general, they are a priori coin-

[8] BP B is assumed to be applicable in case there is no further local occurrence coindexed with the *PRO* element (so-called *arbitrary control*). See von Stechow and Sternefeld (1988).

[9] There have been further attempts to deal with this issue by singling out the proper treatment of *PRO* into a separate theory (*control theory*).

dexed with other non-empty categories and therefore transitively co-determine the antecedent options of anaphoric occurrences of all three binding-theoretic types. In order to adequately capture the binding conditions contributed by empty categories, dealing with decision interdependency (as defined in section 2.2.2) plays an important role, since the a-priori coindexing of these elements can be technically conceived as already performed and, hence, potentially interdepending antecedent decisions. Clearly, however, while a proper algorithmic account of binding should thus be able to accomodate the processing of empty categories, it is evident that, in the application case of robust anaphor resolution, much depends upon the descriptional richness of the employed parser's output.

2.3 Formal requirements upon binding condition verification

As the above discussion has shown, binding theory formally models sets of valid index assignments rather than making predictions on individual instances of anaphoric reference. Hence, it implicitly covers forward as well as backward anaphora. In order to adequately support anaphor resolution, suitable algorithmic accounts of binding should as well cover both cases of anaphora and deal with expressions of all three binding-theoretic types (A, B, and C), which all might play the role of an anaphor or antecedent candidate. Moreover, the implementation of the binding principles should be complete. However, as will become evident in the subsequent survey, some prominent algorithmic approaches to binding comply with these requirements only to a certain extent. The same holds with respect to the more intricate issues of non-finite local domains of binding and, in particular, decision interdependency and empty categories.

3 Algorithmic Approaches to Binding

3.1 Chomsky's original algorithm: the free indexing rule

As part of his original exposition of BT, Chomsky (1981) describes a generate-and-test approach for identifying the subset of index assignments that comply with the binding constraints. As it enumerates *all* possible index assignments and tests them for compliance with BT, this algorithm has a runtime complexity exponential in the number of NPs and empty categories in the surface structure tree. Since it accounts for all issues identified in section 2.2 (including empty categories), this algorithm can be considered a valid implementation of binding. However, as it does not give a detailed account of how to efficiently check for the validity of particular index assignments, it does not directly contribute to solving the problem of BT verification for robust anaphor resolution. Most importantly, however, it does not contribute to referential *disambiguation* as adressed by anaphor resolution in the sense that it considers index assignments valid in which anaphoric entities remain unresolved, as in

(10) The barber$_i$ admits that he$_j$ shaves himself$_j$.

as BT merely enforces the selection of coindexed local governors for type A pronouns, but doesn't enforce coindexing of type B or C occurrences.

Put in a different way, in enumerating all admissible index assignments, free indexing does more than required for anaphor resolution, thus being computationally expensive, while, at the same time, it does less than required as it does not address the issue of identifying index assignments in which anaphoric entities are properly disambiguated.

3.2 The scope of other approaches

Various approaches have been suggested that address the inefficiency and the limited scope of free indexing. Commonly, these approaches circumvent the exponential time complexity of free indexing by restricting themselves to determine *locally* packed representations of the *individual* coindexing options for the occurrence-introducing nodes of the surface structure tree; lists of admissible *combined* index assignments are not generated. This comes at the expense of reduced coverage of the above requirements. In order to identify the most common limitations, four approaches that have received considerable attention in the literature on BT and anaphor resolution will be analyzed in more detail.[10]

3.2.1 The approach of Correa

Correa (1988) employs a single traversal of the parsing tree and combines the assignment of individual sets of admissible antecedent candidates with a simple recency-based antecedent selection rule. In doing so, the conceptual distinction between the computation of admissible index assignments (as addressed by the free indexing rule) and the computation of antecedents (as addressed by anaphor resolution) gets blurred. Moreover, the approach does not cover instances of backward anaphora, and it does not deal with cases of decision interdependency, as mutually incompatible antecedent decisions are not recognized. Furthermore, BP C is not accounted for, and the implementation of BP B can be shown to be only partial. As this algorithm doesn't check for interdepending decisions, empty categories (which are, in general, a priori coindexed with further local occurrences) are not adequately covered either. However, at least it explicitly accounts for cases like *(7c)* above in which anaphors occur in moved elements: the search for configurationally admissible antecedents is extended to cover the original position of the moved element, which is now inhabited by the "*Wh*" trace. Nevertheless, the scope of this account can be shown to be merely partial, as, in cases like the following, it is not taken into account that the moved element itself already contains an (accessible) local subject, and, thus, the binding category of the reflexive pronoun:

(11) [Which of Peter's$_k$ pictures of himself$_k$]$_i$ does John$_j$ like t$_i$?

[10]The results of a related investigation that covers further algorithmic accounts of binding are presented by Branco (2002). However, whereas Branco (2002) considers this issue from a mainly theoretical point of view (e.g., assessing the conceptual repercussions of intragrammatical vs. extragrammatical localization of binding processing), the work presented here focusses on the algorithmic aspects of binding condition verification in the context of robust anaphor resolution.

Clearly, in such cases, wrong results would be obtained if the search for binding-theoretically admissible antecedents were extended to cover the position of the trace. This illustrates that non-finite local domains of binding are not properly dealt with either.

3.2.2 The approach of Ingria and Stallard

Ingria and Stallard (1989), too, stay at the intragrammatical level of computing *locally* packed representations of *individual* admissible coindexings, as they do not address the problem of further referential disambiguation. Hence, they do not resolve the issue of decision interdependency, and, as a consequence, they do not properly account for empty categories. In fact, Ingria and Stallard (1989) themselves identify the lack of an adequate treatment of "*Wh*" traces as one of the major shortcomings of their algorithm (p. 269). However, this approach adequately covers instances of backward anaphora; moreover, the algorithm is particularly efficient and conceptually compelling.

3.2.3 The approach of Giorgi, Pianesi, and Satta

Giorgi et al. (1990) suggest two efficient algorithms for verifying binding conditions. Again, in looking at binding condition verification for type A and type B pronouns from the point of view of *individual* decisions, their approach exhibits the limitation of not resolving instances of interdepending decisions. While they are recognizing the importance of this issue (p. 124): "*[...] it is necessary to put together the constraints that have been separately computed for each item according to principles A and B (and C);*", they nevertheless do not propose an algorithmic solution to this (ibd.) "*problem of BT verification, i.e. whether a given index assignment for the NPs of a sentence complies with the restrictions of BT*". Thus, like the above-discussed approaches, the algorithm of Giorgi et al. (1990) exhibits the shortcoming of not adequatly dealing with empty categories. However, at least this open problem is acknowledged as they discuss the proper treatment of *pro* elements, which is a major issue in their mother language (Italian). Moreover, as already mentioned in section 2.2.5, in suggesting that the local binding of the postponed subject through the respective *pro* element should be considered an admissible exempt case, they provide a partial solution that already covers some of the aspects relevant for dealing with *pro* elements.

3.2.4 The approach of Lappin and McCord

Lappin and McCord (1990b,a) describe an approach employing shared PROLOG variables for modeling reference index distributions, which can be considered a valid solution to the decision interdependency problem based on the PROLOG unification engine. As their grammar covers "*Wh*" traces, these type of empty categories is implicitly accounted for as well. The shared PROLOG variables can be understood as representations of the respective discourse referents. While this approach thus elegantly addresses the issue of decision interdependency and (at least

partially) empty categories, it doesn't make available explicit representations of individual occurrences. As anaphor resolution amounts to more then a mere checking for configurational admissibility, this can be regarded a serious shortcoming, as the local properties of the individual occurrences turn out to be of high relevance as well. Hence, this representation has to be properly extended, which seems to be achieved best outside the original PROLOG framework.

3.3 Binding condition verification for anaphor resolution

The above analysis reveals that prominent algorithmic approaches to binding exhibit serious limitations: (a) in general, as the issue of conflicting individual instances of coindexing is not resolved, the implementation is only partial, and empty categories are not adequately dealt with either; (b) binding principles B and C might be incompletely covered; (c) in addition, the algorithm of Correa (1988) does not deal with backward anaphora. In particular, the problem of referential disambiguation proper is not addressed.

However, if one takes a closer look at the particular requirements of anaphor resolution, as the set-out goal is the determination of *one particular* index assignment that models a plausible referential interpretation, it turns out that it is not required to emulate the *generate all* part of free indexing. Nor is it necessary to compute locally packed representations of all admissible antecedents as done by most of the approaches considered in section 3.2. Rather, it is required to perform referential disambiguation proper, i. e. to compute *one* admissible antecedent for each anaphor, and to employ further means to ensure that the combination of the individual decisions is consistent. Since, however, referential disambiguation generally employs further extragrammatical sources of evidence, this problem should be addressed by properly integrating the binding condition verification algorithm with further anaphor resolution strategies, which are commonly divided into filters and preferences (see Carbonell and Brown (1988)).

4 Anaphor Resolution with Robust BC Verification

Before proceeding with the formal specification of an efficient anaphor resolution algorithm that accomplishes the task of adequately verifying the binding conditions, the issue of robustness deserves further discussion. The above approaches implicitly assume that there is a sole complete and unambiguous surface-syntactic tree over which the computation of the binding conditions is performed. In general, in the scenario of algorithmic anaphor resolution, this requirement will not be met, as robust parsers typically yield fragmentary or ambiguous results.

4.1 Fragmentary syntax

First, there are the various types of *structural ambiguity* that give rise to partial parsing output: uncertainty of syntactic function (involving subject and direct object) and *attachment ambiguities* of prepositional phrases (exemplified by the well-known *telescope* sentences), relative clauses, and adverbial clauses. From the con-

figurational perspective, since, in general, robust state-of-the-art parsers don't yield packed representations of structural ambiguity, these ambiguities typically give rise to *fragmentary syntactic descriptions* which consist of several tree-shaped components. With the exception of the topmost tree fragment, all components correspond to constituents of type PP, S, or NP whose attachment or role assignment failed. Second, *cases in which no reading exists* give rise to fragmentary descriptions comprising the constituents whose combination failed due to constraint violation.[11]

4.2 Verifying binding conditions on fragmentary syntax

Since the binding condition verification procedure refers to the surface-syntactic structure, it is potentially affected through the fragmentation of the parser's output. Thus, in the application context of *robust* anaphor resolution, further efforts are necessary. The first step towards the verification of binding constraints on fragmentary syntax is suggested by the following observation:

> *If both the anaphor and the antecedent candidate are contained in the same connected component of the fragmentary syntactic description, no (direct) binding theoretic evidence is lost.*

In this case, the verification of the binding restrictions of anaphor and antecedent will be possible in a non-heuristic manner, since the necessary positive ($\rightarrow$ binding principle A) and negative ($\rightarrow$ binding principles B, C) syntactic-configurational evidence is entirely available.[12]

However, even in the disadvantageous case in which the anaphor and the antecedent candidate occur in different surface structure fragments, a closer look at the fragments may reveal additional information. In the following example, a typical case is illustrated:[13]

> *(12) Der Mann hat den Präsidenten besucht, der ihn von sich überzeugte.*
> *The man has the president visited, who him of himself convinced.*
> *"The man has visited the president who convinced him of himself."*

Because of the intervening past participle, the relative clause may be interpreted as an attribute to either *Mann* or *Präsidenten*. Hence, syntactic ambiguity arises, yielding a surface structure description which consists of two fragments

```
(S Mann                (S der
   (VP Präsident))        (VP ihn
                             (VP (PP sich))))
```

[11] In both classes of cases, syntactic deficiency results either because the input itself is ambiguous or deficient, or due to shortcomings of the processing resources, e.g. lexicon, grammar/parser, or semantic/pragmatic disambiguation.

[12] This statement, however, solely applies to the direct comparison of the involved occurrences, since in case of further, transitive coindexings, negative evidence stemming from decision interdependency may get lost (cf. section 2.2.2).

[13] The example is given in German because the structural ambiguity comes out more strikingly.

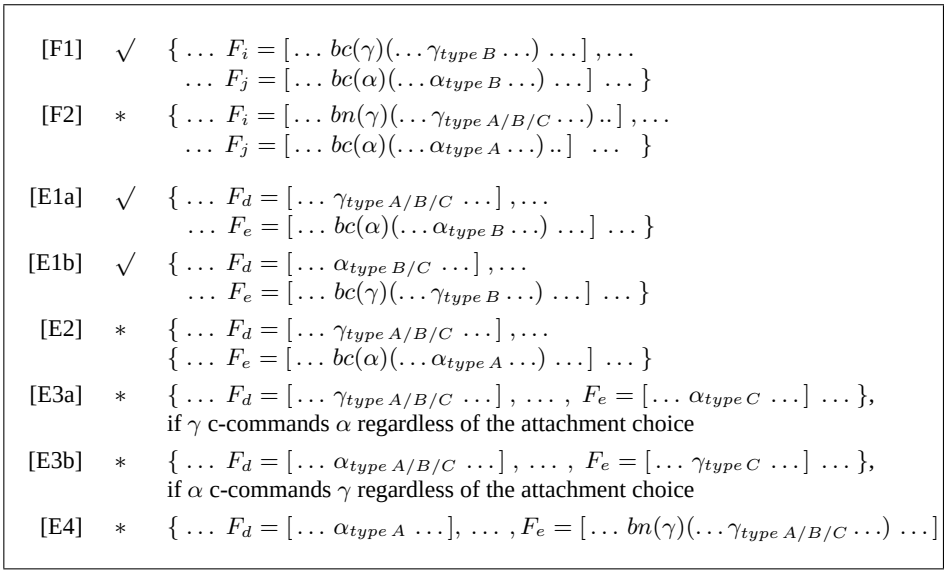

Figure 1: rule patterns for binding constraint verification on fragmentary syntax

In addition, it is known that the second fragment is embedded in the first. There are three pronominal anaphors to be resolved: the reflexive pronoun *sich* of type A, the nonreflexive pronoun *ihn* of type B, and the relative pronoun *der* of type B.

Regarding the reflexive pronoun *sich*, it can be shown that binding theoretic evidence is completely available. Clearly, this holds with respect to the candidates *der* and *ihn*, which are contained in the same surface structure fragment. However, even regarding the two candidates *Mann* and *Präsident* that occur in the other fragment, there is no loss of evidence: since the reflexive pronoun is of binding theoretic type A, and the fragment in which it occurs contains its binding category (the S node of the relative clause), according to binding principle A both candidates may be definitively *ruled out*.

Similar observations can be made regarding the pronouns *ihn* and *der*, for which binding principle B applies: the two candidates *Mann* and *Präsident* are recognized as configurationally *admissible*. In this case, besides the binding category condition, it is decisive that their fragment is known to be *embedded* in the antecedent's fragments.[14]

4.3 Rule patterns

In the subsequent discussion, pairs of anaphors α and antecedent candidates γ are considered that occur in different surface syntactic fragments. The goal consists in determining whether coindexing α and γ (as in case of actually choosing γ as the antecedent of α) complies with the above stated binding-theoretic conditions. Since, according to the definition of the binding conditions, no asymmetric distinc-

[14]It is evident that there are cases in which the latter condition does not hold and the coindexing would violate binding principle C.

[F1]	BP B of α / γ is satisfied	γ does not *locally* bind $\alpha \wedge \alpha$ does not *locally* bind γ
[F2]	BP A of α is violated	γ does not *locally* bind $\alpha \vee \gamma$ does not c-command α
[E1a]	BP B of α is satisfied	γ does not *locally* bind α
[E1b]	BP B of γ is satisfied	α does not *locally* bind γ
[E2]	BP A of α is violated	γ does not *locally* bind α
[E3a]	BP C of α is violated	γ c-commands α
[E3b]	BP C of γ is violated	α c-commands γ
[E4]	BP A of α is violated	γ does not c-command α

Figure 2: binding theoretic background of the rule patterns

tion between anaphor and candidate is drawn, the disjoint reference requirements of both α *and* γ have to be taken into account.

By an abstraction over cases like the ones discussed in section 4.2, a set of *rule patterns* can be designed by means of which the verification of syntactic disjoint reference is generalized in order to make it applicable to fragmentary syntactic descriptions (cf. figure 1).[15] It is distinguished between whether or not it is known that one fragment is subordinated to the other: patterns [E1a] to [E4] only match configurations in which F_d is known to be the *dominating* and F_e the *embedded* fragment; patterns [F1] and [F2], on the other hand, match arbitrary cases. As illustrated by the above example *(12)*, the patterns either make a positive or a negative prediction.[16] One class (five patterns, labeled "$*$") matches cases in which, according to the binding principles, coindexing the anaphor α and the antecedent candidate γ is *ruled out*; the other class (three patterns, labeled "$\surd$") applies in certain cases where there is no violation of any binding principle, and, hence, coindexing is *admissible*. By the binding principles, conditions regarding, on one hand, the *presence or absence of a c-command relation*, and, on the other hand, the *locality or non-locality* of this relation, are stated. The rule patterns are designed to match fragmentary cases in which at least one condition of either anaphor or candidate is violated ("$*$" patterns), or, respectively, cases in which all conditions of anaphor and candidate are satisfied ("$\surd$" patterns). In figure 2, the specific conditions are explicated which the different patterns aim at. There are three patterns that apply in certain cases of BP A violation ([E2]: missing locality; [E4]: missing c-command relation; [F2]: either missing locality or missing c-command relation). Another two patterns cover instances of BP C violation ([E3a], [E3b]: c-command

[15]The following notational conventions are used: round brackets delimit constituents; square brackets emphasize fragment boundaries; $bc(X)$ denotes the binding category of surface structure node X; $bn(X)$ denotes the branching node dominating X according to the c-command definition; the subscript of $X_{type\,Y}$ denotes that the binding theoretic class of the occurrence contributed by X is $Y \in \{A, B, C\}$, e.g. $P_{type\,B}$ is a pronoun. $\surd/*$ indicate the prediction of the respective pattern, i.e. whether, in structural configurations matching the pattern, coindexing is admissible/ruled out.

[16]Example *(12)* illustrates an instance of syntactic fragmentation that is due to structural ambiguity. The rule patterns, however, are general in the sense that they also cover cases of fragmentary syntactic description which are induced by parsing constraint violation (cf. section 4.1).

relation). Moreover, there are three patterns matching cases of BP B satisfaction ([F1], [E1a], [E1b]: non-locality). Two further rule patterns [IEa] and [IEb] (not shown in figure 1) match certain syntactic configurations in which a coindexing would violate the i-within-i condition (see Stuckardt (2001)).

The above collection of rules may be supplemented with further patterns employing more sophisticated conditions regarding the fragments to be matched. As will become evident during evaluation, the choice of rule patterns should depend on the employed parser (see section 4.6). The above set of patterns might suffice if the degree of fragmentation of the parsing results is low.

To illustrate the binding-theoretical background, three rule patterns that match the configurations of the above example *(12)* shall be discussed in detail.[17]

Rule patterns [E1a] and [E1b]

$$\surd \quad \{ \ldots F_d = [\ldots \gamma_{type\ A/B/C} \ldots] , \ldots , F_e = [\ldots bc(\alpha)(\ldots \alpha_{type\ B} \ldots) \ldots] \ldots \}$$
$$\surd \quad \{ \ldots F_d = [\ldots \alpha_{type\ B/C} \ldots] , \ldots , F_e = [\ldots bc(\gamma)(\ldots \gamma_{type\ B} \ldots) \ldots] \ldots \}$$

match certain cases in which it is known that one fragment is (immediately or transitively) subordinated to the other (F_d = dominating fragment, F_e = embedded fragment). [E1a] states that if the fragment of the type B anaphor α is subordinated and it contains the binding category of the anaphor, coindexing with an outside candidate γ (here: arbitrarily of type A, B, or C) is admissible. [E1b], on the other hand, matches cases in which the fragment of the type B (or type C) anaphor α is known to be the dominator; here, a candidate γ of type B that occurs in a fragment containing its binding category is configurationally permitted.[18] Typical cases in which [E1a] and [E1b] apply are instances of structurally ambiguous relative clauses. In the above example *(12)*, since the (embedded) relative clause fragment contains the binding category of the nonreflexive (type B) pronoun occurrences (taken as anaphors α), fragment F_e of rule [E1a] is instantiated; moreover, trivially, the (dominating) main clause instantiates F_d with respect to any of its (type C) occurrences (taken as candidates γ). Hence, [E1a] applies, licensing the respective coindexings. Likewise, pattern [E1b] applies when considering the type C occurrences in the dominating fragment of example *(12)* as anaphors and the type B pronouns in the subordinated fragment as antecedent candidates.

Rule pattern [E2]

$$* \quad \{ \ldots F_d = [\ldots \gamma_{type\ A/B/C} \ldots] , \ldots , F_e = [\ldots bc(\alpha)(\ldots \alpha_{type\ A} \ldots) \ldots] \ldots \}$$

requires that the anaphor's fragment is known to be subordinated; under this condition, the presence of the reflexive pronoun's binding category in the embedded fragment proves to be sufficient for ruling out the candidate as the constructive

[17] For a description of the other patterns, the reader is referred to Stuckardt (2001).

[18] In the case of [E1b], the *anaphor* (i.e. the occurrence to be constructively resolved) occurs in the dominating fragment. Since γ cannot be a local binder of α, the occurrence in the dominating fragment is not allowed to be of type A (cf. the remarks on strong vs. weak coindexing in section 2.2.3). Hence, since α and γ are not interchangeable, [E1a] and [E1b] look slightly different.

antecedent required according to binding principle A. Again, applied to example *(12)*, [E2] rules out the constructive coindexing of the reflexive pronoun with any candidate occurring in the main clause.

4.4 Formal specification of the anaphor resolution algorithm

Based on the above set of rule patterns, an anaphor resolution algorithm can be designed that robustly accomplishes the verification of the binding conditions while complying with the requirements identified in section 2.2 (ROSANA[19] algorithm, see figure 3). In applying a set of *restrictions* (step 1) prior to a set of *preferences* (step 2), the fundamental strategy of Carbonell and Brown (1988) is followed by means of which the candidate set is narrowed down as early as possible. In step 3 of the ROSANA algorithm, the actual *selection* of antecedents takes place. Among the strategies to be applied are restrictions (e.g. morphosyntactic and lexical congruence, disjoint reference conditions) as well as a plethora of preference factors (subject/topicalization salience, syntactic obliqueness, recency, cataphor penalty, parallelism (inertia of syntactic function)) (see Stuckardt (2001) for a further discussion). The subsequent considerations focus on the issue of syntactic disjoint reference; in particular, it shall be explained how the robust verification of the binding conditions is dovetailed with the other anaphor resolution strategies, and how - or, to what extent - the requirements identified in section 2.2 are met.

4.5 Discussion: compliance with the requirements

With respect to the verification of the binding conditions, the central goal of *robustness against fragmentary syntax* is achieved in steps 1b and 3b. As described above, if the considered occurrences are situated in different fragments, the rule patterns come into play; the actual set of patterns to be applied depends on whether it is known that one of the fragments is embedded in the other. Patterns labeled "$*$" are employed to eliminate candidates (steps 1(b)iv and 1(b)v). Patterns marked "$\surd$" are used to *definitively* admit candidates (step 1(b)vi), contrasting the *heuristic* admittance (step 1(b)vii), which entails a plausibility decrement in step 2a.

The issue of *decision interdependency* is addressed in step 3. In explicitely checking for the binding theoretic admissibility of transitively induced coindexings, the algorithm guards against the combination of conflicting coindexings (step 3b). ROSANA thus solves the open problem of "*BT verification*" as identified by Giorgi et al. (1990) while avoiding the exponential time complexity of Chomsky's free indexing rule. In compliance with the above identified requirement to distinguish between *strong (constructive) and weak (non-constructive) verification of BP A*, the decision interdependency test step employs the weak version of this test, which amounts to not blocking *further* (possibly non-local or non-binding) coindexings of type A anaphors. The same distinction is drawn in step 1b: whereas the binding restriction of the anaphor is verified in the strong, constructive sense (step 1(b)i), the candidate's restriction is applied in its weak version (step 1(b)ii). In the rule patterns for the fragmentary case, this subtlety is reflected implicitly in the

[19] ROSANA = **Ro**bust **S**yntax-Based Interpretation of **Ana**phoric Expressions

1. *Candidate Filtering*: for each anaphoric NP α, determine the set of admissible antecedents γ:
   (a) verify morphosyntactic or lexical agreement with γ;
   (b) if the antecedent candidate γ is intrasentential:
      - if α and γ belong to the same syntactic fragment, then verify that
        i. the binding restriction of α is constructively satisfied,
        ii. the binding restriction of γ is not violated,
        iii. no i-within-i configuration results;
      - else (α and γ belong to different syntactic fragments) *try the rule patterns*:
        iv. if one of the patterns [E2], [E3a], [E3b], [E4], or [F2] is matched, then some binding restrictions are violated,
        v. else if one of the two i-within-i rule patterns [IEa] or [IEb] applies, then some binding restrictions are violated,
        vi. else if pattern [E1a], [E1b], or [F1] applies, then the binding restrictions of α and γ are satisfied,
        vii. else (*no rule pattern applies*) assume heuristically that the binding restrictions of α and γ are satisfied;
   (...) Further restrictions might apply (see Stuckardt (2001)).
2. *Candidate Scoring and Sorting*:
   (a) for each remaining anaphor-candidate pair (α_i, γ_j): based on a set of preference heuristics, determine the numerical plausibility score $v(\alpha_i, \gamma_j)$.
   If the binding theoretic admissibility was approved *heuristically* in step 1(b)vii, then reduce the plausibility score $v(\alpha_i, \gamma_j)$ by a constant value;
   (b) for each anaphor α: sort candidates γ_j according to decreasing plausibility $v(\alpha, \gamma_j)$;
   (c) Sort the anaphors α according to decreasing plausibility of their respective best antecedent candidates.
3. *Antecedent Selection*: consider anaphors α in the order determined in step 2c. Suggest antecedent candidates $\gamma_j(\alpha)$ in the order determined in step 2b.
   Select $\gamma_j(\alpha)$ as candidate if there is no interdependency, i.e. if
   (a) the morphosyntactic features of α and $\gamma_j(\alpha)$ are still compatible,
   (b) for all occurrences $\delta_{\gamma_j(\alpha)}$ and δ_α the coindexing of which with $\gamma_j(\alpha)$ and (respectively) α has been determined in the *current* invocation of the algorithm: the coindexing of $\delta_{\gamma_j(\alpha)}$ and δ_α, which results transitively when chosing $\gamma_j(\alpha)$ as antecedent for α, does neither violate the binding principles nor the i-within-i condition, i.e.
      - if $\delta_{\gamma_j(\alpha)}$ and δ_α belong to the same syntactic fragment, then, for both occurrences, verify the respective binding conditions and the i-within-i condition according to steps 1(b)ii and 1(b)iii,
      - else if $\delta_{\gamma_j(\alpha)}$ and δ_α belong to different syntactic fragments, then proceed according to steps 1(b)iv, 1(b)v, 1(b)vi, and 1(b)vii (with the exception of the rule patterns [F2], [E2], and [E4], by means of which binding principle A is *constructively* verified).

   (The case $\delta_{\gamma_j(\alpha)} = \gamma_j(\alpha) \wedge \delta_\alpha = \alpha$ does not need to be reconsidered.)

Figure 3: the ROSANA anaphor resolution algorithm

sense that only regarding occurrence α (taken as the anaphor to be constructively resolved), the strong version of BP A is checked; hence, in the interdependency test step 3b, patterns [F2], [E2], and [E4] are not taken into consideration.

Thus, the issues of decision interdependency and *strong vs. weak verification of BP A* are properly accounted for. Since, in steps 1b and 3b, the *antecedent's* binding condition is verified, the *symmetry of the binding-theoretic predictions* is taken into account as well. Clearly, as there is no asymmetric one-pass tree search, the algorithm adequately deals with instances of cataphora, and the implementation of binding principles A, B, and C can be regarded to be complete.

It shall now be discussed whether - or, to what extent - the ROSANA algorithm accounts for the various types of *empty categories*. In providing a mechanism for efficiently checking for decision interdependency, ROSANA properly handles the a priori coindexings of "*Wh*" traces, *pro* elements, and *PRO* elements. Furthermore, the BC verification step of ROSANA might be straightforwardly adapted in order to achieve an adequate processing of *pro* instances. These occurrences are binding-theoretically interpreted just like ordinary type B pronouns, but with two exceptions: (a) no antecedent search takes place; (b) it is *not* checked whether there is a binding of postponed occurrences through their respective *pro* expletives (see the discussion of the above examples *(8b)* and *(8c)*). Likewise, *PRO* elements are just considered as ordinary (depending upon type of control) type A or B occurrences for which no antecedent is sought, but which might themselves play the role of antecedents. The sole issue not covered by the current ROSANA BT verification mechanism that seems to necessitate a considerable extension regards the treatment of anaphors occurring *inside* moved elements as discussed above (examples *(7c)* and *(11)*) and partially taken into account by the algorithm of Correa (1988).

Typically, robust state-of-the-art parsers do not yield surface-structural descriptions containing empty categories because, for instance, the general algorithmic recognition of instances of "*Wh*" movement or the decision whether a particular *PRO* occurrence is controled by the subject or the object are intricate problems that are known to involve knowledge well beyond the surface-syntactic level. However, the central point to note here is that the ROSANA BT verification algorithm, while being efficient, fulfils all main requirements of an adequate processing of these types of occurrences (as far as they are made available by the parser), and hence has a considerably broader scope than the other approaches discussed in section 3.

Finally, regarding *non-finite local domains of binding*, the ROSANA algorithm covers them as well. In general, the output of robust state-of-the-art parsers is sufficiently informative so that cases like *(6a..d)*, in which a possessive marker has to be interpreted as a logical subject, can be recognized and properly processed. However, further efforts are required in order to deal with more intricate cases such as (in German) adjectivally employed participles, where it might be necessary to assume the presence of an empty occurrence (a priori coindexed with the dominating NP) that represents the logical subject of the local domain. Essentially, these empty occurrences should be treated like empty categories; once again, the mechanism that checks for decision interdependency does most of the job.

4.6 Evaluation

Obviously, the direct evaluation of the BC verification strategy employed by any anaphor resolution algorithm imposes a problem, as much depends upon the chosen parser, and as, by now, no generally accepted evaluation corpus comprising test cases that cover all of the above identified requirements is available. Hence, an indirect, *extrinsic* evaluation will be carried out, looking at the problem of anaphor resolution in general, and determining the cases in which wrong antecedents are assigned *due to the failure of the above specified robust BC verification algorithm*. In the implementation put under scrutiny here, ROSANA works on the partial syntactic descriptions generated by the robust FDG (Functional Dependency Grammar of English) parser of Järvinen and Tapanainen (1997), which are further processed in order to integrate them with the data structures proper of referential processing (occurrences, discourse referents). The evaluation is carried out on a referentially annotated corpus of 35 news agency press releases, comprising 12904 words.[20]

A qualification of the failures of anaphor resolution gives evidence that, with respect to the fragmentary descriptions generated by the chosen parser, the robust implementation of syntactic disjoint reference is nearly optimal. None of the 7 incorrect antecedent choices that are due to failures of the disjoint reference strategy (out of a total of 246 wrong antecedent choices for the evaluation corpus) are due to wrong predictions of the (still partly heuristic) algorithmisation of the binding theoretic restrictions; rather, they are caused by wrong (in contrast to fragmentary, i.e. partial) parsing results: while already employing defensive parsing strategies, the parser still overgenerates in certain cases. In 6 of the 7 disjoint reference failures, a configurationally admissible candidate has been erroneously eliminated; in the remaining case, a configurationally forbidden candidate has been erroneously approved. Hence, there is a tendency of overgenerating disjoint reference restrictions. A detailed analysis reveals that, in 4 of the 6 cases, the respective parsing error consists in a wrong interpretation of a structurally ambiguous relative clause. This indicates that, while the rate of disjoint reference failure is already very low (2.8% of all failures), a small improvement might be achieved by employing a more defensive parsing strategy with a slightly higher level of fragmentation, which, by now, amounts to an average of 2.61 fragments per sentence. It further illustrates that, as mentioned in section 4.3, the choice of rule patterns for robust syntactic disjoint reference should depend on the employed parser: a higher degree of parse fragmentation might give rise to extending the set of patterns.

5 Conclusion

According to the above analysis, the ROSANA BT verification algorithm can be considered to meet almost all of the requirements identified in section 2.2. Contrary to its competitors, the different binding principles and types of anaphora (forward

[20]The anaphor and coreference resolution results proper are provided in Stuckardt (2001) and at the ROSANA website: *http://www.stuckardt.de/rosana.htm*.

vs. backward) are adequately covered, and, most importantly, the problems of *BT verification* and *referential disambiguation proper* are solved: it is taken care of that (a) the computed index *distributions* (*combinations* of antecedent decisions) are valid, and that (b) every anaphoric occurrence is assigned an antecedent. This is accomplished by integrating the BT verification algorithm with a set of further filtering and preference strategies, thus guiding the antecedent selection process in order to arrive at a *single*, highly plausible, and valid index *distribution*, and, hence, avoiding the exponential time complexity of the free indexing rule. Regarding its extrinsic performance on the output of the robust parser of Järvinen and Tapanainen (1997) with respect to the task of anaphor resolution, it turned out that there is not much space for further improvement. Moreover, the algorithm proved to be computationally inexpensive. Thus, the practical requirements in the context of incomplete preprocessing are met as well.

Seen from a different perspective, the approaches of Correa (1988), Ingria and Stallard (1989), and Giorgi et al. (1990) chiefly address the efficiency issue of free indexing, which is resolved by restricting the considerations to the computation of *locally* packed representations of referential ambiguity (sets of configurationally admissible antecedent candidates of individual occurrences) and hence at the expense of not checking the *overall* validity of decision combinations. The ROSANA algorithm achieves efficiency *and* fully-fledged referential disambiguation; this, however, comes at the expense of restricting the output to a *single* valid index assignment. Thus, is natural to ask whether an efficient algorithm might be designed that computes *non-locally* packed representations of binding-theoretically valid *combinations* of coindexings (index distributions), which can be considered the reference processing analogues of the packed shared forests that are employed for the lossless representation of ambiguous parses. In fact, declaratively encoding the BC verification in a sufficiently powerful unification-based formalism implicitly achieves this goal. From a theoretical point of view, such approaches might even be considered to exhibit a higher degree of robustness, as unification-based representations elegantly integrate different sources of grammatical evidence, which might all contribute to referential disambiguation (see Stuckardt (1997)).

References

Branco, António. 2002. Binding Machines. *Computational Linguistics* 28(1), 1–18.

Carbonell, Jaime G. and Brown, Ralf D. 1988. Anaphora Resolution: A Multi-Strategy Approach. In *Proceedings of the 12th International Conference on Computational Linguistics (COLING)*, pages 96–101.

Chomsky, Noam. 1981. *Lectures on Government and Binding*. Dordrecht: Foris Publications.

Chomsky, Noam. 1986. *Knowledge of Language*. New York: Praeger.

Correa, Nelson. 1988. A Binding Rule for Government-Binding Parsing. In *Proceedings of the 12th International Conference on Computational Linguistics (COLING)*, pages 123–129.

Giorgi, Alessandra, Pianesi, Fabio and Satta, Giorgio. 1990. A Computational Approach to Binding Theory. In *Proceedings of the 13th International Conference on Computational Linguistics (COLING)*, pages 120–125.

Hobbs, Jerry R. 1978. Resolving Pronoun References. *Lingua* 44, 311–338.

Ingria, Robert J. P. and Stallard, David. 1989. A Computational Mechanism for Pronominal Reference. In *Proceedings of the 27th Annual Meeting of the Association of Computational Linguistics (ACL)*.

Järvinen, Timo and Tapanainen, Pasi. 1997. A Dependency Grammar for English. Technical Report TR-1, Department of General Linguistics, University of Helsinki.

Kennedy, Christopher and Boguraev, Branimir. 1996. Anaphora for Everyone: Pronominal Anaphora Resolution without a Parser. In *Proceedings of the 16th International Conference on Computational Linguistics (COLING)*, pages 113–118.

Lappin, Shalom and Leass, Herbert J. 1994. An Algorithm for Pronominal Anaphora Resolution. *Computational Linguistics* 20(4), 535–561.

Lappin, Shalom and McCord, Michael. 1990a. Anaphora Resolution in Slot Grammar. *Computational Linguistics* 16(4), 197–212.

Lappin, Shalom and McCord, Michael. 1990b. A Syntactic Filter on Pronominal Anaphora for Slot Grammar. In *Proceedings of the 28th Annual Meeting of the Association for Computational Linguistics (ACL)*, pages 135–142.

Mitkov, Ruslan. 1998. Robust Pronoun Resolution with Limited Knowledge. In *Proceedings of the 17th International Conference on Computational Linguistics (COLING'98/ACL'98), Montreal*, pages 869–875.

Pollard, Carl and Sag, Ivan A. 1994. *Head-Driven Phrase Structure Grammar*. Stanford: CSLI Publications.

Stuckardt, Roland. 1997. Resolving Anaphoric References on Deficient Syntactic Descriptions. In *Proceedings of the ACL Workshop on Operational Factors in Practical, Robust Anaphor Resolution for Unrestricted Texts*, pages 30–37.

Stuckardt, Roland. 2001. Design and Enhanced Evaluation of a Robust Anaphor Resolution Algorithm. *Computational Linguistics* 27(4), 479–506.

von Stechow, Arnim and Sternefeld, Wolfgang. 1988. *Bausteine syntaktischen Wissens.*. Westdeutscher Verlag.