Specification and Verification of Binding Constraints: an integrated account*

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Abstract

Binding constraints form one of the most robust modules of grammatical knowledge. They have resisted, however, to be neatly integrated into grammar specification and to receive a full implementation. We argue that the ultimate root for this is to be found in the current coindexation-driven rationale for their specification and verification. As an alternative, we propose a semantics-driven approach which, while permitting a unification-based specification of binding constraints, allows for a verification methodology that supports a lean implementation of binding theory.

1 Introduction

Binding constraints delimit the relative positioning of anaphors and their admissible antecedents in grammatical geometry. From an empirical perspective, they stem from quite robust generalizations and exhibit a universal character, given their parameterized validity across natural languages. From a conceptual point of view, in turn, the relations among binding constraints involve non-trivial symmetry, which lends them a modular nature. Accordingly, they have been considered one of the most robust modules of grammatical knowledge, usually known as binding theory.

1.1 Specification

The specification of binding constraints has been the focus of intense research in last decades, from which a binding theory of increased empirical adequacy has emerged. Recent developments of (Pollard and Sag, 1994, Chap.6), indicate that there are four of such constraints (vd. (Xue, Pollard, and Sag, 1994), (Branco and Marrafa, 1999)):

(1) *Principle A:* A locally o-commanded short-distance reflexive must be locally o-bound.

Lee$_i$ thinks [Max$_j$ saw himself$_{*i/j}$].

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Principle Z: An o-commanded long-distance reflexive must be o-bound.

[O amigo do Rui$_i$]$_j$ acha que o Pedro$_k$ gosta dele próprio$_{*i/j/k}$.
[the friend of_the Rui] thinks that the Pedro likes of_he PRÓPRIO

'[Rui's friend]$_j$ thinks that Pedro$_k$ likes him$_j$/himself$_k$.' (Portuguese)

Principle B: A pronoun must be locally o-free.

Lee$_i$ thinks [Max$_j$ saw him$_{i/*j}$].

Principle C: A non-pronoun must be o-free.

[Kim$_i$'s friend]$_j$ thinks [Lee saw Kim$_{i/*j}$].

These constraints are defined on the basis of some auxiliary notions. The notion of *local domain* involves the partition of sentences and associated grammatical geometry into two zones of greater or less proximity with respect to the anaphor. Typically, the local domain coincides with the predication domain of the predicator subcategorizing the anaphor. In some cases, there may be additional requirements that the local domain is circumscribed by the first upward predicator that happens to be finite, bears tense or indicative features, etc..

O-command is a partial order under which, in a clause, the Subject o-commands the Direct Object, the Direct Object o-commands the Indirect Object, and so on, following the usual obliqueness hierarchy of grammatical functions, being that in a multiclausal sentence, the upward arguments o-command the successively embedded arguments.

The notion of *o-binding* is such that x o-binds y iff x o-commands y and x and y are coindexed, where coindexation is meant to represent anaphoric links.[1]

1.2 Verification

In contrast to the attention devoted to their specification, the issue of verifying the compliance of grammatical representations with binding constraints has not deserved an equally attentive scrutiny. As a consequence, the formal and computational handling of these constraints presents considerable resistance when it comes to their full integration into grammar.

As we discuss in detail below, the mainstream methodology for the verification of binding constraints, first proposed in (Chomsky, 1980, 1981), requires extra-grammatical processing steps of non-tractable complexity which, moreover, deliver a forest of indexed trees to anaphor resolvers.

More recently, constraint-based grammatical frameworks have not been equipped with satisfactory alternatives. In LFG, the account of binding constraints requires special purpose extensions of the description formalism (Dalrymple, 1993), though ensuring only a partial handling of these constraints.

As to HPSG, no formal integration of binding constraints into grammar is offered. It is interesting to note that in the nine page Appendix of (Pollard and Sag, 1994), the fragment of grammar developed and discussed along this book is fully specified using the HPSG description

[1]There are anaphors that are subject-oriented, in the sense that they only take antecedents that have the grammatical function Subject. Some authors (e.g. Dalrymple (1993)) assume that this should be seen as an intrinsic parameter of binding constraints and aim at integrating it in their definition. In this point we follow previous results of ours reported in (Branco, 1996), where the subject-orientedness of anaphors is argued to be, not an intrinsic feature of binding constraints, but one of the surfacing effects that result from the non linear obliqueness hierarchy associated to some predicators (or to all of them in some languages).

formalism. Binding constraints receive a definition in Chapter 6, but are the only part of grammatical knowledge discussed in the book that escapes such formal encoding.

While pointing out the fact that these constraints are waiting to be accommodated into HPSG grammars, Backofen et al. (1996, p.65) and Bredenkamp (1996) subsequent elaboration on this issue implied that some kind of essential limitation of the description formalism for representing grammatical knowledge might have been reached[2] — a suggestion we seek to contradict in the present paper.

Our primary goal here is thus to bridge the gap between the grammatical nature of binding constraints and their full integration into grammar so that the effective coverage of constraint-based grammars is extended and integrates binding theory. In particular, we aim at achieving this by using a lean description formalism, and by ensuring both an empirically adequate specification and a tractable verification of binding constraints.

As a first step, in Section 2, we underline the distinction, seldom taken into account, between specification and verification of binding constraints. We will then review advances proposed in the literature concerning the latter. We observe that three major lines of progress can be identified with respect to the verification task: packaging of anaphoric ambiguity, packaging of non-locality, and lexicalization of binding constraints.

Building on these contributions, in Section 3 we discuss their harmonization. We suggest that a more accurate comprehension of the nature of binding constraints is an important step towards this goal. On the basis of such revision, and adopting an underspecified representation of the semantics of anaphors, we introduce the rationale of a new, integrated account for the specification and verification of binding constraints.

In Section 4, in the light of this new methodology, we show how binding constraints can be fully integrated into grammar. We provide a modular specification of binding theory in terms of the HPSG description formalism and discuss the basic requirements of its implementation in an implemented formalism such as ProFIT (Erbach, 1995).

Section 5 is devoted to the discussion of the results contributed in this paper and to a consideration of the lines of research possibly open by these contributions.

2 The Coindexation-driven Paradigm

The specification of binding constraints have greatly evolved in the last decades, being one of the major research issues in theoretical linguistics. In contrast, the more practical issue of their verification has received a much less principled scrutiny, despite the fact that, also here, relevant problems remain to be studied. As a consequence, the device of coindexation for marking anaphoric links, and supporting the verification of their compliance with binding constraints, has remained quite stable. This device is at the heart of the mainstream approach for verifying these constraints and has been adopted in the different variants of this approach.

The first formulation of a verification procedure based on coindexation dates back to (Chomsky, 1980, 1981), which set the stage for subsequent research on this topic. The basics of this procedure can be outlined as follows:

[2] Bredenkamp (1996, Chap.7) presents a detailed discussion of some apparent options to encode binding constraints in HPSG — coindexation as an unbounded dependency construction vs. type hierarchy to classify anaphors according to their anaphoric realization vs. type hierarchy to classify predicators in terms of the anaphoric realization of their arguments — and of their shortcomings.

(2) After the grammatical parsing of a sentence with n NPs has been completed, for every parse tree t:

i. *indexation:* generate a new, annotated tree by assigning indices to the NPs in t;

ii. *filtering:* store this annotated tree if the indexation of NPs respects binding constraints, otherwise delete it;

iii. *iteration:* repeat i.–ii. until all type-different assignments of n possibly different indices have been exhausted.

As noted as early as in (Correa, 1988), this approach is non-tractable, having Fong (1990) showed in detail that it is of exponential complexity. Moreover, this methodology implies the conceptual awkwardness of having a module of grammar, the set of binding constraints, that is not made operative during the grammatical processing, but as an extra-grammatical add-on.[3]

On a par with these problems, this proposal disregards also any concern with interfacing grammar with systems for reference processing. The input for such systems will not be a grammatical representation to be refined vis-à-vis the preferences for anaphor resolution, but a forest of differently labeled trees that have to be internally searched and compared with each other by anaphor resolvers.

2.1 Packaging anaphoric ambiguity

A first proposal for improving the coindexation-driven methodology was due to Correa (1988). His effort was directed towards enhancing the integration of binding constraints into grammar and obtaining a practically tractable procedure.

Simplifying some details, the proposed algorithm can be outlined as follows:

(3) Let t be a constituency tree where every NP has a type-distinct index. Start from the top of t with two empty stacks, A and B, where indices will be collected, respectively locally c-commanding[4] indices and non-locally c-commanding indices; when an NP_j is found:

i. *copy:* leave a copy of A (if NP_j is a short-distance reflexive) or B (if it is a pronoun) at the NP_j node;

ii. *assign:* take the first index i of the stack copied into NP_j node, and annotate NP_j with j=i;

iii. *collect:* add index j to A.

When a local domain border is crossed:

iv. *reset:* reset B to A $\cup$ B.

This algorithm was given two different implementations, one by Correa (1988), the other by Ingria and Stallard (1989). Further elaboration by Giorgi, Pianesi, and Satta (1990),

[3] Correa (1988) observed that although the integration of binding constraints "into rules which may be used to derive structure that already satisfies the [constraints] is not a straightforward task" (p.123), that should be the path to follow, a point also strongly stressed in subsequent elaboration on this issue by Merlo (1993).

[4] C-command is a configurational version of the command relation where x c-commands y iff the first branching node that dominates x dominates y (Barker and Pullum, 1990).

and Pianesi (1991), offered a variant of this algorithm in terms of formal language techniques, where the stack copied into pronouns contains the antecedent candidates excluded by principle B.

The "do-it-while-parsing" approach of Correa's implementation has the advantage of discarding a special-purpose postgrammatical module for binding. That implementation, however, turns out to be dependent on a top-down parsing strategy. On the other hand, Ingria and Stallard's implementation has the advantage of being independent of the parsing strategy adopted. This was done however at the cost of still requiring a special-purpose postgrammatical parsing module for binding.

Besides the issue of bringing binding theory into grammar, it is worth noticing that this evolution inside the coindexation-driven methodology presented other significant improvements. If one disregards step (ii) — a disguised recency preference mixed with binding constraints — and considers the result of verifying these constraints to be the assignment to an NP of the set of indices of its grammatically admissible antecedents, then it is possible to discard the proliferation of indexed trees as a way to express anaphoric ambiguity. Moreover, this packaging of anaphoric ambiguity provides for a neat interface with anaphor resolvers, whose preferences will then pick the most likely antecedent candidate from the relevant stack of indices.

These advances permit a verification procedure of tractable complexity ((Correa, 1988, p.127), (Giorgi, Pianesi, and Satta, 1990, p.5)). This results crucially from the move towards the lexicalization of the constraining effect of binding principles, a solution also adopted in subsequent proposals by other authors, as we will discuss below. The binding constraint of each anaphor is now enforced independently of how the surrounding anaphors happen to be resolved. This implies that there is no need to anticipate all the different resolutions for all the relevant anaphors with a process of exhaustive coindexation. It implies also that cases of undesired transitive anaphoricity are handled by other filters during the anaphor resolution process.[5]

These positive results on the side of the verification task seems however to be obtained at the cost of some negative consequences on the side of the specification and empirical adequacy. The algorithm above is acknowledged not to be able to cope with constraints involving non-local dependencies. Principle C is not accounted for, and the anaphoric potential of anaphors complying with Principle B is only partially accommodated. As stack B only contains indices of the non-local c-commanders — not all indices except those of the local c-commanders — the constraining effect of Principle B is not correctly accounted for. Also backwards anaphora or cross-over cases are not handled (vd. (Correa, 1988, p.127), (Ingria and Stallard, 1989, p.268)).

2.2 Packaging non-locality

Other contributions to improve the coindexation-driven approach are due to Dalrymple (1993) and Johnson (1995). Instead of being directed to packaging ambiguity as the one above, they have in common being concerned with packaging non-locality.

[5]Consider sentence *John said that he shaved him.* Ignoring how other anaphors are resolved, in the light of binding constraint B, *he* can take *John* as its antecedent; likewise, *him* can take *John* as its antecedent. Nevertheless, if *he* actually ends up resolved against *John*, the latter cannot be the antecedent of *him*, and vice-versa. This specific resolution both of *he* and *him* blocks two anaphoric relations that would otherwise have been admissible. It induces a contingent violation of binding constraint B due to an accidental, transitive anaphoric relationship between *he* and *him*.

2.2.1 Replication of trees in nodes of trees

Johnson's algorithm is embodied in Prolog code. Abstracting away from details associated to that format, it gets the following outline:

(4) Let t be a constituency tree where every NP has a type-distinct index. For every NP_i in t, traverse the tree from NP_i upwards until the top node is reached. When a locally c-commanding NP_j is found:

i. annotate NP_i with i=j if NP_i is a short-distance reflexive,

ii. annotate NP_i with i≠j if NP_i is a non-reflexive;

When a non-locally c-commanding NP_j is found,

iii. annotate NP_i with i≠j if NP_i is a non-pronoun.

Although this outline renders the algorithm in a bottom-up fashion, Johnson ingeniously developed an implementation of it that is independent of the parsing strategy by resorting to delaying mechanisms. Consequently, in spite of its postgrammatical flavor, that implementation does not require postgrammatical processing, thus bringing the task of binding constraints verification into grammar processing.

These results were obtained with some accessory devices: Each node in the tree is "conceptualized as a pair consisting of a tree and a vertex in that tree"(Johnson, 1995, p.62). Consequently, the whole tree where a given NP appears is locally accessible to be "walked up" since its replica is present at the pair (Category, Tree), which is the NP node itself.

This algorithm improves the coindexation methodology in terms of efficiency as it does not resort to exhaustive indexation. This is possible, however, at the cost of highly complicating the grammatical representation due to the replication of the whole tree at each one of its nodes.

Nevertheless, even avoiding exhaustive indexation, this approach does not fully get rid of the proliferation of trees and ensures a neat interface with reference processing. For a given reflexive with more than one admissible antecedent, each different antecedent candidate corresponds to a different coindexation and, consequently, to a different tree. That is what generally happens with long-distance reflexives, but it may happen also with short-distance ones, as in the example (5) below.

As to the interface with reference processing, problems arise with reflexives and non-reflexives, though of different nature. Reflexives, if ambiguous, give rise to proliferation of trees thus requiring comparison between trees in the subsequent process of anaphor resolution. As to non-reflexives, typically ambiguous, their analysis does not give rise to proliferation of trees, but does not capture their ambiguity either. This is so because they end up associated with negative information, i.e. information about what NPs cannot be their antecedents. The index of a pronoun is made unequal with the indices of its local c-commanders, it is not made equal with its grammatically admissible antecedents. The same holds for non-pronouns with respect to c-commanders. Consequently, in the case of non-reflexives, the task of determining the antecedent candidates that satisfy the relevant binding constraint is to a large extent still to be completed.

2.2.2 Equations with regular expressions

The LFG account of binding, set forth in (Dalrymple, 1993), resorts to a different approach to generalize over the possible non-locality of anaphoric dependencies. It uses lexical inside-out equations, a special-purpose extension of the LFG description formalism which may include regular expressions,[6] as in (7) below, where an example with a long-distance reflexive, the Chinese *ziji*, is presented:

(5) John$_i$ described Bill$_j$ to himself$_{i/j}$.
himself: $((\text{OBL}_{Goal}\uparrow)\ \text{SUBJ})_\sigma = \uparrow_\sigma \vee ((\text{OBL}_{Goal}\uparrow)\ \text{OBJ})_\sigma = \uparrow_\sigma$

(6) * John described Bill$_i$ to him$_i$.
him: $((\text{OBL}_{Goal}\uparrow)\ \text{OBJ})_\sigma \neq \uparrow_\sigma$

(7) Zhangsan$_i$ yiwei [Lisi$_j$ yiwei [...ziji$_{i/j/...}$...]].
Zhangsan$_i$ thought [Lisi$_j$ thought [...him$_{i/j/...}$...]].
ziji: $((\text{OBJ}^*\uparrow)\ \text{SUBJ})_\sigma = \uparrow_\sigma$

The right-hand side of the equation stands for the semantic representation ('σ') of the f-structure ('$\uparrow$') of the anaphor. The left hand side stands for the semantics of the antecedent: In (7) the long-distance reflexive is an Object in a f-structure where one of the possibly many upward Subjects is the antecedent.

Although initial skepticism about the tractability of these equations was dissipated by Kaplan and Maxwell (1988), the survey by Backofen et al. (1996) reports that no implemented LFG grammar was known to handle binding.

It is worth pointing out that no single generalization concerning its binding capacity can be formally associated to a given anaphor, as several equations have to be defined for every anaphor. Each equation specifies concrete grammatical functions for a given anaphor and its possible antecedent, but either the anaphors or the antecedents may occur with one of a range of several grammatical functions (see a minimal example in (5)). Besides, it is not defined how non-lexical NPs (e.g. anaphoric definite descriptions, ruled by Principle C) may be assigned the corresponding equation.

However these difficulties turn out to be solved, the LFG variant of the coindexation-driven approach presents the same sort of problems of Johnson's proposal.

The interfacing of grammar with reference processing is problematic as the proliferation of representations is not avoided. The ambiguous reflexives end up represented by several different grammatical representations. These representations correspond to the satisfaction of different equations for the same anaphor, involving different grammatical functions, as in (5), or result from the several existential interpretations of functional uncertainty in the case of long-distance reflexives, as in (7).

Likewise, the anaphoric capacity of pronouns and non-pronouns, typically ambiguous, is not represented. There is only one f-structure resulting from the universal interpretation of negative equations associated with these type of anaphors. No information about their possible antecedents complying with the relevant binding constraint is provided.

[6] Koenig (1999) introduces a device in HPSG description formalism for stating inside-out constraints. This suggestion helps to make an HPSG emulation of the LFG variant of the coindexation-driven approach for the verification of binding constraints.

Finally, it is worth noting that other problems can also be pointed out, that are specific of this LFG account of binding.

One of these problems emerges from the fact that the positive equations for reflexives do not require identity of indices of anaphorically related expressions, but instead impose identity of semantic representations. This incorrectly enforces any type of anaphora (bound, bridging, e-type, etc.) to the sole mode of coreference.

Another problematic issue was identified by Bredenkamp (1996, p.96). Binding constraints exhibit a universal character given their validity across languages, provided that the convenient parameterization of the auxiliary notions involved in their definition (cf. Section 1.1) is ensured. In this sense, there seems to be a loss of generalization in this LFG account inasmuch as binding constraints cannot be stated in their own in the individual grammars, still less to be "reused" from one to the other and be part of the core constraints of an eventual universal grammar. In fact, their constraining effect turn out to be crafted into the several inside-out equations in the grammars.

3 A Semantics-driven Paradigm

The contributions assessed above share a common point of departure with regards the verification algorithm first proposed by Chomsky (1980, 1981), thus solving some of its more significant drawbacks. The move towards the lexicalization of binding constraints represents an important shift in the verification strategy: Verifying binding constraints is not a matter of inspecting final grammatical representations, but instead a matter of some local operation triggered by information lexically associated with anaphors about their anaphoric class. This allowed to bring binding constraints verification into grammar processing, and permitted tractable verification procedures.

From the discussion in the previous Section, it follows also that these contributions were only partially successful in overcoming other problems of the coindexation-driven methodology. Being partially successful, the contributions mentioned above, however, brought to the fore essential dimensions of binding that have to be concomitantly accounted for. Accordingly, an alternative methodology for binding constraints verification has to find a way to harmonize all these different aspects — lexicalization, anaphoric ambiguity packaging and non-local context packaging — while giving a suitable answer to the issues of a correct empirical coverage and a neat interfacing of grammar and anaphor resolution.

Against this background, a breakthrough depends, on our view, on changing some entrenched primitives underlying the conception of binding constraints. In the previous Section we underlined the distinction between the issues of specification and verification of binding constraints, so that the latter could be isolated and better assessed. We argue now that further improvements on it depend on bridging back this distinction and possibly changing the way one understands the specification of binding constraints itself.

3.1 Patterns in the semantics of anaphors

Binding constraints have been basically viewed as well-formedness conditions, thus belonging to the realm of Syntax: "[they] capture the distribution of pronouns and reflexives" (Reinhart and Reuland, 1993, p.657). In line with (Gawron and Peters, 1990), however, we think these constraints should rather be understood as conditions on semantic interpretation, given they delimit (non-local) aspects of meaning composition, rather than aspects of syntactic composition.

Note that, like other kind of constraints on semantic composition, binding constraints impose conditions on the interpretation of certain expressions — anaphors, in the present case — based on syntactic geometry. This cannot be seen, however, as implying that they express grammaticality requirements. By replacing, for instance, a pronoun by a reflexive in a sentence, we are not turning a grammatical construction into an ungrammatical one, even if we assign to the reflexive the antecedent adequately selected for the pronoun. In that case, we are just asking the hearer to try to assign to that sentence a meaning that it cannot express, in the same way as what would happen if we asked someone whether he could interpret *The red book is on the white table* as describing a situation where a white book is on a red table.

In the example above, given how they happen to be syntactically related, the semantic values of *red* and *table* cannot be composed in a way that their sentence could be used to describe a situation concerning a red table, rather than a white table. Likewise, if we take *John thinks Peter shaved him*, given how they happen to be syntactically related, the semantic values of *Peter* and *him* cannot be composed in a way that this sentence could be used to describe a situation where John thinks that Peter shaved himself, i.e. Peter, rather than a situation where John thinks that Peter shaved other people, e.g. Paul, Bill, etc., or John himself. The basic difference between these two cases is that, while in the first the composition of the semantic contributions of *white* and *table* (for the interpretation of their NP *white table*) is constrained by local syntactic geometry, in the latter the composition of the semantic contributions of *John* and *him* (for the interpretation of the NP *him*) is constrained by non-local syntactic geometry.

This discussion leads one to consider that, semantically, an anaphor should be specified in the lexicon as a function whose argument is a suitable representation of the context — providing a semantic representation of the NPs available in the discourse vicinity —, and delivers an update both of its anaphoric potential – which is instantiated as the set of its grammatically admissible antecedents – and of the context, against which other NPs are interpreted. Naturally, all in all, there will be four of such functions available to be lexically associated with anaphors, each corresponding to one of the different four classes of anaphors, in accordance with the four binding constraints A, Z, B or C.

3.2 Binding nominals

This rationale is in line with the insights of (Johnson and Klein, 1990) concerning the processing of the semantics of nominals, and also the spirit (but by no means the letter) of the dynamic semantics framework (Chierchia, 1995). It provides a suitable ground for the harmonization of the different advances put forward in the literature concerning the integration of binding theory into grammar. It can also be the basis for an integrated account of the specification and verification of binding constraints.

Note that the relevant input context may be represented under the form of a set of three lists of reference markers, **A**, **Z** and **U**. List **A** contains the reference markers of the local o-commanders of n ordered according to their relative grammatical obliqueness; **Z** includes the o-commanders of n, possibly observing multiclausal obliqueness hierarchy; and **U** is the list of all reference markers in the discourse context, including those not linguistically introduced.

The updating of the context by an anaphoric nominal n may be seen as consisting simply in the incrementing of the representation of the former, with a copy of the reference marker (Kamp and Reyle, 1993) of n being added to the three lists above.

The updating of the anaphoric potential of n, in turn, delivers a representation of the contextualized anaphoric capacity of n under the form of the list of reference markers of its admissible antecedents. This list results from the binding constraint, associated to n, being applied to the relevant representation of the context of n.

Given this setup, the role of binding constraints in circumscribing the anaphoric potential of nominals is explicitly acknowledged. The particular contextualized realization of that potential and the verification of binding constraints coincide and consist in a few simple steps. If the nominal n is a short-distance reflexive, its semantic representation is updated with **A'**, where **A'** contains the reference markers of the o-commanders of n in **A**. If n is a long-distance reflexive, its semantic representation includes **Z'**, such that **Z'** contains the o-commanders of n in **Z**. If n is a pronoun, $\mathbf{B}=\mathbf{U}\backslash(\mathbf{A'}\cup[\text{r-mark}_n])$ is encoded into its representation, where r-mark$_n$ is the reference marker of n. Finally if n is a non-pronoun, its updated semantics keeps a copy of $\mathbf{C}=\mathbf{U}\backslash(\mathbf{Z'}\cup[\text{r-mark}_n])$.

Note that these lists **A'**, **Z'**, **B** and **C** collect the reference markers that are antecedent candidates at the light only of the relevant binding constraints, which are relative positioning filters in the process of anaphor resolution.[7] Their elements have to be submitted to the other filters and preferences of this process so that one of them ends up being chosen as the antecedent. In particular, some of these markers may turn up not being admissible antecedent candidates due to violation of other filters — e.g. those requiring similarity of morphological features and of semantic type — that on a par with binding constraints have to be complied with. For example, in the slight variant of (5), *John described Mary to himself*, by the sole filtering effect of Principle A, $\{\text{r-mark}_{John}, \text{r-mark}_{Mary}\}$ is the set of antecedent candidates of *himself*, which will be narrowed down to $\{\text{r-mark}_{John}\}$ when all the other filters for anaphor resolution have been taken into account.[8]

Separating these two type of filters — similarity of morphological features and binding constraints — seems to be a correct option, required by examples with split antecedents. In an example of this type, such as *John told Mary they would eventually get married*, where *they* is resolved against *John* and *Mary*, the morphological features of the anaphor are not identical to the morphological features of each of its antecedents, though the relevant binding constraint applies to each of them (Higginbotham, 1983). As discussed in (Eschenbach et al., 1989), in the case of plural anaphors, their set of antecedent candidates after the verification of binding constraints should receive further processing before other filters and preferences apply. The reference markers in that set, either singular or plural, should be combined into other plural markers in the way of i-sums a la Link (1983).

It is easy to acknowledge that, while following an empirically grounded conception of binding constraints, this approach embodies, and harmonizes, the major contributions of previous proposals concerning the verification of these constraints. It builds on specific strategies for the packaging of anaphoric ambiguity (vz. list of reference markers) and non-local context (vz. set of lists of reference markers). Concomitantly, it supposes the lexicalization of binding

[7]See (Branco, 1999, Chap.2) for a list of filters and preferences for anaphor resolution proposed in the literature.

[8]In this respect we deviate from the proposal of (Pollard and Sag, 1994), where the token-identity of indices is meant to be forced upon the anaphor and its antecedent in tandem with the relevant binding constraint.

constraints. Moreover, this is achieved avoiding the above reported problems related to the proliferation of grammatical representations and to computational intractability,[9] as well as the problem of the interfacing grammar with reference processing.

What remains to be discussed is whether, given this new format for the verification of binding constraints, their specification and integration into grammar can still be made with currently affordable formal and computational tools.

4 An HPSG/UDRT Exercise

This new approach to binding constraints can receive an easy and principled integration into formal grammar. In what follows, we outline how the module of binding theory can be specified and handled in a constraint-based grammatical framework such as HPSG.

As a proposal for that integration, we designed an extension to the UDRT semantics component for HPSG of Frank and Reyle (1995). This component is encoded as the value of feature CONT(ENT), which is now enhanced with feature ANAPH(ORA). This new feature keeps information about the anaphoric potential of the corresponding nominal *n*: its subfeature ANTEC(EDENTS) keeps record of how that potential is updated when the anaphor enters a grammatical construction; and its subfeature R(EFERENCE)-MARK(ER) indicates the reference marker of *n*, to be contributed to the context.

On a par with this extension, and still assuming (Pollard and Sag, 1994) feature geometry as a starting point, also the NONLOC value is extended with a new feature, BIND(ING), with subfeatures LIST-A, LIST-Z, and LIST-U. These lists provide a specification of the relevant context and correspond to the lists **A**, **Z** and **U** above. Subfeature LIST-LU is a fourth, auxiliary list for encoding the contribution of local context to the global, non-local context.[10]

Given this adjustment to the grammatical geometry, the lexical definition of a pronoun, for instance, will include the following SYNSEM value:

(8)
$$\left[\begin{array}{ll}
\text{LOC}\,|\,\text{CONT} & \left[\begin{array}{ll}
\text{LS} & \left[\begin{array}{ll}\text{L-MAX} & \boxed{1}\\ \text{L-MIN} & \boxed{1}\end{array}\right]\\
\text{SUBORD} & \{\}\\
\text{CONDS} & \left\{\left[\begin{array}{ll}\text{LABEL} & \boxed{1}\\ \text{ARG-R} & \boxed{2}\end{array}\right]\right\}\\
\text{ANAPH} & \left[\begin{array}{ll}\text{R-MARK} & \boxed{2}\\ \text{ANTEC} & \mathit{principleB}\left(\boxed{4},\boxed{3},\boxed{2}\right)\end{array}\right]
\end{array}\right]\\
\text{NONLOC}\,|\,\text{BIND} & \left[\begin{array}{ll}
\text{LIST-A} & \boxed{3}\\
\text{LIST-Z} & \mathit{list}\\
\text{LIST-U} & \boxed{4}\\
\text{LIST-LU} & \boxed{2}
\end{array}\right]
\end{array}\right]$$

[9] At worst list appending and list complementation are the operations involved at each node of a tree for a string of length *n*, which can be carried out in time $O(n^2 log(n))$.

[10] Given this extension of SLASH feature, the coordination constraint requiring token-identity of SLASH values of conjuncts should be refined in order to involve only its original subfeatures INHER and TO-BIND.

In this feature structure, the contribution of the its reference marker for the context by the pronoun is ensured via token-identity between R-MARK and LIST-LU values. The piling up of this reference marker in the global LIST-U value is determined by a new HPSG principle specific to binding (cf. (9) below).

The binding constraint associated to pronouns, in turn, is specified as the relational constraint *principleB*. This relational constraint is responsible for the updating of the anaphoric potential of the pronoun as it enters a grammatical construction. When its arguments are instantiated, this constraint returns list **B** as the value of ANTEC. It is defined to take (in first argument) all markers in the discourse context, given in LIST-U value, and remove from them both the local o-commanders (included in second argument) of the pronoun and the marker corresponding to the pronoun (in third argument).

The SYNSEM of other anaphors, ruled by Principles A, C or Z, are similar to the one above.[11] The crucial difference lies in the relational constraints in ANTEC value. These constraints encode the adequate binding principles — *principleA*, *principleC* and *principleZ* — and return the updated anaphoric potential under the form of a list — **A'**, **C** or **Z'**, respectively —, along the lines discussed in the previous Section.

We turn now to the specification of the context, i.e. the values of LIST-A, LIST-Z, LIST-U and LIST-LU. This representation can be handled by means of a new HPSG principle we termed the Binding Domains Principle. This principle consists of three clauses constraining signs with respect to these lists of reference markers. Due to space limitations, we illustrate only part of this principle in full detail below, with its Clause I, for LIST-U and LIST-LU. The full specification of Binding Domains Principle can be found in (Branco, 1999, Chap.6):

(9) **Binding Domains Principle**, Clause I

i. LIST-LU value is identical to the concatenation of LIST-LU values of its daughters in every sign;

ii. LIST-LU and LIST-U values are token-identical in a sign of sort *discourse*;

iii. i. LIST-U value is token-identical to each LIST-U value of its daughters in a non-NP sign;

ii. in an NP sign *k*:

- in Spec-daughter, LIST-U value is the result of removing the elements of LIST-A value of Head-daughter from the LIST-U value of *k*;
- in Head-daughter, LIST-U value is the result of removing the value of R-MARK of Spec-daughter from the LIST-U value of *k*.

By virtue of (i.), LIST-LU collects up to the outmost sign, which is designed to be of sort *discourse*, the markers contributed for the context by the different NPs. Given (ii.), they are passed to LIST-U at this sign . And (iii.) ensures that they are propagated to every NP. Subclause (iii.ii) is meant to avoid a self-reference loop due to anaphoric interpretation, which is known in the literature as the i-within-i effect.

The HPSG top ontology was thus extended with the new subsort *discourse*: $sign \equiv word \vee phrase \vee discourse$. This new type of object corresponds to sequences of sentential signs, for

[11]Binding constraints for non-lexical anaphoric nominals are lexically stated in the corresponding determiners.

which a specific Immediate Dominance schema has to be provided, and at which reference markers from the non-linguistic context may be introduced.

As to the other two Clauses of Binding Domains Principle, they are designed to constraint LIST-A and LIST-Z values. Briefly, Clause II ensures that LIST-A value is passed from the lexical head to its successive projections, and also from the head-daugthers to their arguments. Concomitantly, at the lexical entry of any predicator p, LIST-A is defined as the concatenation of the R-MARK values of the subcategorized arguments of p, specified in its ARG-S value. Note that exemption occurs when $principleA(\boxed{1},\boxed{2})$ is the empty list, in which case the anaphor resolver operating on that list should find an antecedent for the reflexive outside any binding constraint (Pollard and Sag, 1994, p.263)

Clause III ensures that, at the top node of the grammatical representation, LIST-Z is set up as the LIST-A value of that sign. Moreover, it ensures that LIST-Z is successively incremented at the suitable downstairs nodes — those defining successive locality domains for binding — by appending, in each of these nodes, LIST-A value with LIST-Z value of the upstairs node.

From this description of Binding Domains Principle, it follows quite naturally that the locus in grammar for the parameterization of what counts as a local domain for a given language is the specification of Clause II and III for that language.

This exercise of specifying a binding theory for HPSG that complies with the semantic-driven rationale for binding constraints put forward in the previous Section was worked out in a computational implementation using ProFIT (Erbach, 1995). In this computational grammar the relational constraints coding binding principles were implemented by means of Prolog predicates associated to the lexical clauses of anaphoric expressions. These relational constraints for binding were straightforwardly defined in terms of simple auxiliary predicates ensuring the basic component operations of list appending, list difference, etc.

It is of note that some of these auxiliary predicates have arguments, e.g LIST-U, whose value is obtained when the whole relevant grammatical representation is built up. As expected, this is a consequence of accumulating and packaging non-local information in such lists. Like in Jonhson's approach, this imposes that some delaying device is used in the evocation of those predicates, which in this implemented grammar was done by resorting to the Prolog built-in predicate `freeze/2`.

5 Discussion and Outlook

5.1 Lexicalization and underspecification

The above unification-based account of binding constraints reconciles specification and verification in the sense that the semantics-driven rationale set up in Section 3 found an accommodation in HPSG such that no verification procedure specific to binding theory is required other than the general procedure to verify ordinary grammatical constraints of the HPSG description formalism. Note also that, while this account provides for an integration of binding into grammar specification and processing, it ensures computational tractability and does not resort to representational proliferation to encode anaphoric ambiguity.

These formal and computational results are obtained without any special-purpose extension of the description formalism, but also without loss of empirical adequacy in the predictions ensured by binding constraints. For every anaphor of the different four binding classes, the corresponding binding requirement is correctly secured and its anaphoric ambiguity is fully represented.

Empirical adequacy extends also to a suitable handling of anaphoric links for anaphora of all types. Once a given reference marker **x** is identified as the antecedent, out of the set of antecedent candidates, it can be related with the marker **y** of the corresponding anaphor by means of an appropriate DRS condition in the CONDS value. Such a condition models the specific type of anaphora at stake. For instance, coreference will require the expected condition **y**=**x**, while an instance of bridging anaphora[12] may be modeled by **y**=*brid*(**x**), where *brid* stands for the relevant bridging function, etc.[13]

On a par with these results on their formal and empirical aspects, binding constraints are also accommodated by doing justice to the role they appear to play in natural language grammar. Coping with this desideratum is possible given a clear separation between the relevant parameterization factors and binding constraints proper is ensured. Accordingly, the generalizations of universal character encoded by these constraints can be uniformly read off from the specification of the grammars for particular languages.

The conceptual soundness of this account extends also to the common wisdom about the division of labor between grammars and anaphor resolvers. This approach provides for a suitable hooking up of the grammatical module of binding with, possibly non-grammatical, modules for anaphor resolution and reference processing. Feature ANTEC is the neat interface point between them, and its value has just to be cut down by anaphor resolvers until the most likely antecedent be possibly isolated. Given that the semantic relation between antecedent and anaphor markers can be specified simply as another DRS-condition in CONDS value, a DRT/HPSG representation for the resolved anaphoric link is available and the integration of anaphor resolution outcome into grammatical representation is neatly secured.

5.2 Essential incrementability

As acknowledged in the previous sections, these results are built on contributions in the literature whose efforts and shortcomings we interpreted as pointing towards crucial dimensions in the understanding of binding that were in need to be harmonized so that a new step forward could be achieved:

- Lexicalization: Binding constraints are properties of anaphoric expressions determining how their semantic value can be composed or co-specified, under a non-local geometry, with the semantic value of other expressions. Accordingly, their proper place in grammar specification is at the lexical description of the relevant anaphoric items.
- Underspecification: Binding constraints delimit how the anaphoric potential of anaphors can be realized when they enter a grammatical construction. On the one hand, this realization is not a final solution in terms of circumscribing the elected antecedent, but a space of grammatically admissible solutions. On the other hand, this realization of anaphoric potential has to be decided, locally, in terms of non-local information. Accordingly, an underspecification-based strategy is required to pack ambiguity and non-locality.

[12]Under the mode of bridging (indirect or associative) anaphora, an anaphor may refer to an entity that is e.g. an element or part of the denotation of the antecedent, or an entity that includes the denotation of the antecedent, etc. See (Poesio and Vieira, 1998) for a recent discussion.

[13]Vd. (Branco, 1999, Chap.5) for a detailed elaboration on this issue.

At this juncture we have access to an equation of the binding problem that may help to elucidated possible open research issues. The important point to note is that there might be something specific to the underspecification strategy mentioned above.

Notice that underspecification in the usual sense is meant to ensure that all possible solutions are present to be sieved down until the more appropriate one is possibly fixed. This is what could be termed as decremental underspecification.

In contrast, the process of packaging non-local context and anaphoric potential seems to require a different type of underspecification which can be deemed as incremental. Here, the solution space is essentially open, not to be narrowed down yet, but to be incrementally enlarged.

The discussion of a concrete example may help to clarify the point at stake. Consider the following two expressions, where the first one corresponds to a stage before the completion of the utterance of the second one.

(10) if he$_{\mathbf{i}}$ appears on time, John$_{\mathbf{i}}$ will

(11) If he$_{\mathbf{i/j}}$ appears on time, John$_{\mathbf{i}}$ will meet Bill$_{\mathbf{j}}$ today.

For the sake of the argument, let us assume that *he* happens to be sententially bound. In the grammatical representation of (10), feature ANTEC, which encodes the underspecified representation of the anaphoric reference of *he*, should have the single marker [r-mark$_{John}$]. Nevertheless, when the utterance is completed, as in (11), ANTEC value should rather be [r-mark$_{John}$, r-mark$_{Bill}$]. This illustrates the incremental nature of this underspecified piece of grammatical information.

Note that in the HPSG exercise reported in the previous section, if the Immediate Dominance schema for discourse signs is prepared to cope with non-sentential discourse units, one gets the expected representation of the anaphoric capacity of the pronoun in both examples above. In any of these two cases, the computation of LIST-U value, upon which the value of ANTEC depends, is delayed until a first dominance dependency from a discourse node is found.

Although this provides the correct outcomes, we think it does not make justice to the incremental nature of the natural process. It may happen that a human pauses in (10). In such a case, he can thereafter proceed to (11) and finish the utterance, successfully resuming the interpretive task, admittedly incrementing the natural correlates of [r-mark$_{John}$] to those of [r-mark$_{John}$, r-mark$_{Bill}$]. In contrast, something similar is not possible with the HPSG fragment above. In what concerns at least the LIST-U and ANTEC values, the grammatical representation obtained for (10) would have to be overridden in order to obtain the incremented representation for (11), an option not available. The representation for (11) has to be built up from scratch, it cannot be obtained from the incrementing of the representation of (10).[14]

This argument builds on examples of utterance continuation, such as (10) and (11), but it may find further empirical support in the cases of accidental transitive anaphoric links (vd. Section 2.1 above). In these cases, it is apparent that the outcome of the constraining effect of

[14]Note that this discussion may be also illuminating in what concerns implementation alternatives to the approach that uses delaying mechanisms. Getting at every relevant point of the parsing process an updating of the lists locally encoding the non-local context, if possible, implies the overhead of re-doing at every such point the calculations required by the binding constraints that happen to apply at the different NPs already parsed.

a binding constraint for a given nominal may be re-calculated given the way other anaphors in the context turn out to be resolved. This seems to provide further evidence implying an essential incremental nature in the processing of binding constraints.

We think there may be here an interesting research issue which the account of binding reported in this paper helps to bring to light. It seems to touch on an important feature of natural language processing whose understanding and modeling may help to enhance the robustness of grammars.

6 Conclusions

Departing from the coindexation-driven paradigm, we proposed an alternative, semantics-based rationale for the specification and verification of binding constraints. Under this rationale, these constraints are viewed as contributing to circumscribe the contextually determined semantic value of anaphors. This approach helped to find a principled and modular integration of binding theory into constraint-based grammars. It permitted a specification format that avoids resorting to non-lean formalisms, and a verification methodology of tractable complexity, thus allowing the extension of the empirical coverage of implemented grammars based on an explicit, constraint-based representation of linguistic knowledge.

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