On Formalization of Word Order Properties*

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Abstract. This paper contains an attempt to formalize the degree of word order freedom for natural languages. It exploits the mechanism of the analysis by reduction and defines a measure based on a number of shifts performed in the course of the analysis. This measure helps to understand the difference between the *word order complexity* (how difficult it is to parse sentences with more complex word order) and *word order freedom* in Czech (to which extent it is possible to change the word order without causing a change of individual word forms, their morphological characteristics and/or their surface dependency relations). We exemplify this distinction on a pilot study on Czech sentences with clitics.

1 Introduction

In this paper we are suggesting a formal treatment suitable for languages with higher degree of word order freedom. This phenomenon, although very important for the complexity (and success) of parsing algorithms, seems to be neglected by the formal theory. The languages with higher degree of word order freedom tend to achieve worse parsing results even when identical parsing methods are applied. The stochastic methods or methods of machine learning exploited in parsing do not answer the question whether the freedom of word order is really the crucial phenomenon which not only theoretically, but also practically constitutes the greatest parsing challenge.

We are not aiming at any particular parsing algorithm or system; instead, we would like to clarify some basic features and notions which may play a role in the investigations of the word order freedom. We are going to exploit the method of analysis by reduction and the formal data type derived from this method, so-called D-trees. A complete description of both the method and the data type can be found for example in [10].

The word order variations in a particular language can be divided into two major groups – those which affect word forms in a sentence (and their morphological or even syntactic categories) and those which don't. The first group may be illustrated for example by the differences between an active and passive sentence:

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Peter bought a book for Maria yesterday.
A book was bought by Peter for Maria yesterday.

Because English is a language with very sparse number of word forms derived from a single lemma, the changes of the word order are accompanied by insertions or deletions of functional words or prepositions. This mechanism is common also in some languages with richer inflection and higher degree of word order freedom, as e.g. in Czech.

This type of word order variations does not constitute a good basis for the investigation of word order freedom, because too many factors are involved. The latter group is more interesting from our point of view: the constraint that the word forms and their morphological and syntactic properties should not be changed together with the change of a particular word order, helps to study and measure the word order freedom separately from other phenomena. Let us look at the set of examples for both languages mentioned above:

English allows only variations of the word order position of the temporal complementation, e.g.:

Peter bought a book for Maria yesterday.
Yesterday Peter bought a book for Maria.

Czech allows substantially more permutations, for example:

Petr koupil včera Marii knihu.
Petr včera koupil Marii knihu.
Petr Marii koupil včera knihu.
Petr Marii včera koupil knihu.
Marii Petr koupil včera knihu.
Marii Petr včera koupil knihu.
Knihu Petr koupil Marii včera.
Knihu Marii koupil Petr včera.
Knihu koupil Petr včera Marii.
Knihu včera koupil Petr Marii.
Včera koupil Petr Marii knihu.
Včera koupil knihu Marii Petr.
Včera Petr Marii koupil knihu.
Včera knihu Marii koupil Petr.
...

These sentences have the same syntactic structure (apart from the word order) – the same morphological (case, number, gender, tense, ...) and syntactic categories (Subject, Predicate, Direct or Indirect Object, ...) are assigned to individual words.[1] On the basis of these examples it seems that a simple measure of a degree of word order freedom could be related to a number of permutations preserving the above mentioned properties.

Although very natural, this measure would have two substantial drawbacks. The first one is a certain *gray zone* existing especially in languages with higher degree of word order freedom (and higher number of possible permutations) in which it is very difficult to judge individual permutations because they may be acceptable only in a very obscure reading. The second issue is related to the fact that the maximal number of permutations in a sentence with n words reaches $n!$ – a number too big for a manual enumeration of all variants.

In this paper we propose a different approach. It is based both on a sound theoretical and formal background as well as on syntactically annotated data. The

[1] These sentences differ in their communicative dynamism – what is an 'old information' referring to a previous context and what is a 'new information', i.e., the 'core' of the message.

theoretical background has already been described for example in [6,10], where a formal model of a stratificational dependency approach to natural language description is proposed and further enriched. The model is based on an elementary method of analysis by reduction (AR, see [6], here Sect. 2.2). The analysis by reduction has served as a motivation for a family of so called *restarting automata*, see [9].

In order to demonstrate how the proposed measure of word order freedom works, we are going to apply it to selected sentences from the Prague Dependency Treebank (PDT),[2] a large-scale treebank of Czech, based on the theory of the Functional Generative Description [11].

2 The Background

2.1 Functional Generative Description

The theoretical linguistic basis for our research is provided by the Functional Generative Description (FGD in the sequel), see esp. [11]. FGD is characterized by its stratificational and dependency-based approach to the language description.

The *stratificational approaches* split language description into layers, each layer providing complete description of a (disambiguated) sentence and having its own vocabulary and syntax. As we focus on surface word order phenomena in this project, we make use of three *surface layers* of FGD only:[3]

a**-layer** (analytical layer) capturing surface syntax in a form of a labeled dependency tree (non-projective in general); the most important information being an *analytical function*, i.e., surface syntactic function of a node (as e.g. Subject, Object, Attribute);

m**-layer** (morphological layer) capturing morphology, i.e., a string of triples [word form, lemma, tag] for each word or punctuation mark in a sentence;

w**-layer** (word layer) capturing individual words and punctuation marks in a form of a simple string.

Individual items of these three layers straightforwardly reflect individual words and punctuation marks in a sentence – there is an one-to-one correspondence between individual symbols of the w- and m-layer (we leave aside small exceptions here) and between individual symbols of m- and a-layer. We will refer to triples of items from all three layers corresponding to a single occurrence of a word form as to a *lexical bundle* in the sequel.

FGD as a *dependency-based approach* describes surface syntactic information in a form of dependency trees (Sect. 3.1; see also [8]). Individual words of a sentence are represented as nodes of the respective dependency tree, each node

[2] `http://ufal.mff.cuni.cz/pdt.html`

[3] We disregard here the *tectogrammatical layer*, which captures deep syntax comprising language meaning – the core concepts of this layer being dependency, valency, and topic-focus articulation.

being a complex unit capturing the lexical, morphological and syntactic features; relations among words are represented by oriented edges. The dependency nature of these representations is very important particularly for languages with relatively high freedom of word order – the dependency trees are generally able to treat the word order in a natural and transparent way.

2.2 Basic Principles of the Analysis by Reduction

Analysis by reduction (AR) is based on a stepwise simplification of an analyzed sentence. It defines possible sequences of reductions (deletions) in the sentence – each step of AR is represented by deleting (at least) one word of the input sentence.[4] Consequently, it is possible to derive formal dependency relations between individual sentence members based on the possible order(s) of reductions, see also [10]; very comprehensive overview of the problem can be found in [1], see also for further references there.

Using AR, we analyze an input sentence (w-layer) enriched with the metalanguage information from the m- and a-layers. Symbols on different layers representing a single word of an input sentence (lexical bundles) are processed simultaneously. A sentence is simplified until so called *core structure* is reached (typically its predicate).

The principles of AR on the surface layers can be summed up in the following observations:

- The fact that a certain word (or a group of words) can be deleted implies that this word (or group of words) *depends in* AR on one of the words retained in the simplified sentence; the latter being called *governing word(s) in* AR. In other words, the governing word(s) has/ve the syntactic distribution identical to the entire combination of the governing and the dependent words.
- Two words (or groups of words) can be deleted in an arbitrary order if and only if they are *mutually independent in* AR.[5]
- In order to ensure correctness of the simplified sentence (see below), certain groups of words have to be deleted in a single step (e.g., a preposition and the corresponding noun; a finite verb plus its auxiliaries); such words are said to constitute a *reduction component*. Even in such cases, it is usual to determine governing-dependent pairs on the layer of surface syntax (a-layer). In such a case, it is necessary to define (rather technical) special rules for particular language phenomena.
- In specific cases, an operation *shift* consisting in shifting of a word form to another word order position is used to ensure correctness of the simplified sentence.

When simplifying an input sentence, it is necessary to apply certain elementary constraints assuring adequate analysis on the surface layers:

[4] For the purposes of this article, we leave aside possible rewriting steps, which are necessary for an adequate analysis on the tectogrammatical layer of the FGD.

[5] Here we focus on dependency relations and we disregard non-dependency relations as esp. coordination and apposition.

1. principle of *correctness*: a grammatically correct sentence must remain correct after its simplification;
2. principle of *shortening*: at least one word (i.e., its correlates on *w*-, *m*- and *a*-layer) must be deleted in each step of AR;
3. principle of *generalization*: a simplified sentence must preserve an overall meaning of the original sentence;
4. principle of *minimality*: each step of AR must be 'minimal': any potential reduction step concerning less symbols in the sentence would violate the principle of correctness on the *w*-layer.

The basic principles of AR can be illustrated on the following Czech sentence:

(1)	*Marii*	*se*	*Petr*	*tu knihu*	*rozhodl*	*nekoupit.*
	to-Mary	REFL	Peter	that/the book	decided	not-to-buy

'To Mary, Peter decided not to buy the book.'

Let us look more closely at several possible reduction steps. For example, it is clear that the demonstrative pronoun *tu* 'that/the' has to be deleted prior to the noun *knihu* 'book' – otherwise, the simplified sentence would not be correct, e.g. **Marii se Petr tu rozhodl nekoupit.* '*To Mary, Peter decided not to buy the.' It implies that the pronoun depends on the noun according to the AR principles. The dependency relation is represented as the edge [*tu*, *knihu*] in the dependency tree.

Similarly, the noun *knihu* 'book' must be reduced prior to the verb *nekoupit* 'not-to-buy' (as **Marii se Petr tu knihu rozhodl.* '*To Mary, Peter decided the book.' is an incorrect simplification) and thus the noun depends on the verb.

On the other hand, *Marii* 'to-Mary' and *knihu* 'book' can be reduced in an arbitrary order, thus these words are mutually independent.

We can continue in the same manner until the sentence is reduced to the pair *Se rozhodl.* '(He) decided.' However, the simplified sentence is not a correct Czech sentence – the reflexive morpheme *se* is a clitic and thus it has to be located in the 'second position' in a correct sentence.[6] For this reason, the shift operation is applied which results in a correct simplified sentence *Rozhodl se.* '(He) decided.'

This pair represents a core structure as it cannot be further simplified; technical rules are applied for creating the edge (a verb being always a governor for its REFL clitic), see [6].

Figure 1 shows the resulting structure describing the previous sentence. It consists of the surface non-projective syntactic *a*-tree, of the string of triples [word form, lemma, tag] on the *m*-layer and of the string of word forms (with their translation) on the *w*-layer. The dotted lines interconnect corresponding nodes.

[6] In Czech, clitics have specific constraints on their surface word order position: they occupy so called *Wackernagel's position*: roughly speaking, the position after the first prosodic unit; its syntactic description can be found in [3], see also Sect. 4.

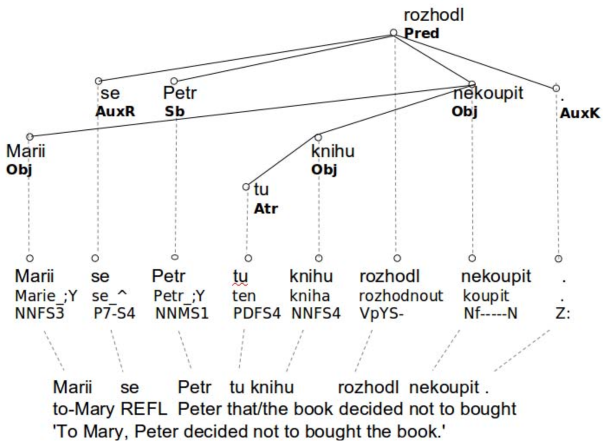

Fig. 1. Sentence (1) – representation on a-, m- and w-layers according to FGD

3 Formalization of Basic Notions

3.1 Delete/Dependency Trees (D-trees) and Characteristic Sentence

One of the important factors of our formalization of word order freedom is a choice of an appropriate data type. In this paper we work with tree structures denoted as a (surface or analytical) D-trees (Delete or Dependency trees), see e.g. [10]; D-tree is a rooted ordered tree with edges oriented from its leaves to its root. Nodes of each tree correspond to individual occurrences of word forms in a sentence. Moreover, we suppose a total ordering on the nodes that reflects word order in a sentence.

This means that each node of a D-tree is a pair $[i, a]$, where a represents an input word (referred to as a *lexical part of a node*) and i denotes a word order position in a sentence (called a horizontal index).

In fact, this version of D-tree actually constitutes a special case of a DR-tree introduced in [10] which does not consider rewriting. The complete formal definition of a D-tree can be found in the same paper.

The concept of D-tree reflects the analysis by reduction (AR) (without rewriting) – its structure corresponds to a way how individual words of a sentence are deleted in the course of the corresponding steps of the analysis by reduction. Each edge of a D-tree connects a word form $[i, a_i]$ to some other word form $[j, a_j]$, which cannot be deleted earlier then $[i, a_i]$ in (any branch of) analysis by reduction of the same sentence.

The root of such a D-tree is one of the nodes corresponding to the word forms which remain in the sentence after the last reduction step of AR.

For the investigation of the word order freedom it is also necessary to limit our scope and to exclude sentences which would bring into the play different phenomena than the word order. Let us therefore limit our considerations to *correct* *sentences* of a natural language and their *correct syntactic and morphological analysis* based on the principles of FGD.

First, we can naturally integrate all relevant information from the FGD surface layers into a single D-tree. With respect to the one-to-one correspondence between items of the three surface layers, we assign all a-, m-, and w- information for an individual word form (or punctuation mark) to a single node of a D-tree; such a D-tree is referred to as a *(correct) surface* D*-tree* (see Fig. 2 for a correct surface D-tree for sentence (1)).

A set of such surface trees is denoted as CT.

We refer to a string $w = a_1, \ldots, a_n$ corresponding to a correct surface D-tree as to a *(correct) characteristic sentence.* Thus, a (complex) symbol $a_i, i \in \{1, \ldots, n\}$, reflects a word form enriched with the relevant information from each of a-, m-, and w-layers – we call such a complex symbol a *lexical bundle*. For example, the lexical bundle for the word form *rozhodl* 'decided' consists of the word form itself (w-leayer), from its analytical function `Pred` (a-leayer), and its lemma *rozhodnout* 'to decide' and morphological tag `VpYS-` (m-leayer), see Fig. 2.

3.2 Measures of Non-projectivity

When considering word order freedom, we have to take into account one phenomenon which is common in languages with higher degree of word order freedom, namely non-projective constructions (for previous usage of this term see esp. [7,5]). In order to classify this phenomenon, it is necessary to define certain notions allowing for an easy definition of projectivity/non-projectivity and also for the introduction of useful measures of non-projectivity (these notions are formally defined in [4]).

The *coverage of a node u of a* D*-tree* identifies nodes from which there is a path to u in the D-tree (including empty path). It is expressed as a set of horizontal indices of nodes directly or indirectly dependent upon a particular node. For example, the coverage of the node of the verb *nekoupit* in Fig. 2 consists of the horizontal indices of nodes representing the words *Marii, tu, knihu, nekoupit.*

The notion of a coverage leads directly to a notion of *a hole in a subtree.* Such a hole exists if the set of indices in the coverage is not a continuous sequence. In Fig. 2 there is only a single subtree with at least one (actually two) hole in its coverage, the subtree rooted in the verb *nekoupit.*

We say that D-tree T is *projective* if none of its subtrees contains a hole; otherwise, T is *non-projective.*

3.3 Shift Operation

In order to be able to describe necessary word order shifts in the course of AR, we need to define a notion of equivalence for D-trees. Such equivalence (denoted as DP-equivalence) is defined as follows: DP-*equivalent trees* are those D-trees which have (i) the 'same' sets of nodes, i.e., the nodes have identical lexical parts and may differ only in their horizontal indices, and (ii) their edges always connect 'identical' pairs of nodes (nodes with identical lexical part). It actually means

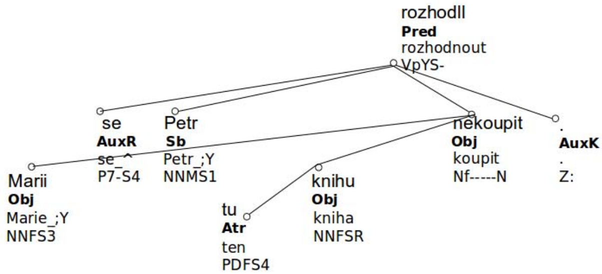

Fig. 2. Sentence (1) – correct surface D-tree

that a particular set of DP-equivalent trees contains the D-trees representing sentences created by a permutation of the words of the original sentence but having the same dependency relations.

Let T be a D-tree; the set of D-trees which are DP-equivalent to T will be denoted DPE(T). In other words, DPE(T) is a set of D-trees which differ only in the word order of their characteristic sentence.

The previous concepts allow us to introduce a new feature, a *number of reduction steps enforcing a shift* in a single branch of AR. Shifts make it possible to change word order and thus 'recover' from incorrect word order that may be incurred by an AR deleting step. The *shift operation* is such a change in a D-tree when (i) the ordering of all nodes except for one is preserved, and (ii) the edges are preserved (connecting 'identical' pairs of nodes with respect to their lexical parts). It means that both the original D-tree T and the modified one belong to the same set DPE(T).

Let T be a D-tree, $T \notin \mathsf{CT}$. Our goal is to find – if possible – a modified D-tree T' such that T' is a correct surface tree (i.e., $T' \in \mathsf{CT}$) and T' is DP-equivalent to T (i.e., $T' \in \mathsf{DPE}(T)$) by applying as small number of shift operations as possible.

4 Pilot Study on Czech Sentences

4.1 Description of the Experiment

In our experiment we are focusing on a development of a measure of word order freedom based upon the notions defined or introduced in previous sections and upon the data available in the Prague Dependency Treebank (PDT). Using the treebank is very important for a number of reasons, especially:

- It gives us a large representative sample of syntactically annotated sentences which can be used for the development and testing of the proposed measure.
- The annotated data from the treebank are independent of our experiments and thus we don't have to discuss whether a particular sentence should have been annotated in this or that way, we take the annotation as a given objective fact.

The analysis of data from the Prague Dependency Treebank gave very interesting results from the point of view of word order freedom. According to [2], almost one quarter of sentences from PDT 1.0 contains non-projective constructions. More precisely, among the 73 088 sentences of training data in PDT 1.0, there are 23.2 % non-projective ones, i.e., 16 920 sentences. These sentences can be divided into the following categories:

1. non-projectivity given by a modal verb (or a verb with similar properties) with an infinite complementation . . . 5 696 non-projectivities in 4 708 trees;
2. compound prepositions . . . 5 894 non-projectivities in 5 388 trees;
3. adjectives . . . 963 non-projectivities in 922 trees;
4. comparatives . . . 379 non-projectivities in 369 trees;
5. others . . . 10 938 non-projectivities in 8 045 trees.[7]

Out of these categories, verbal non-projectivities are very interesting from the linguistic point of view while the second most frequent category, compound prepositions, contains mostly very technical and linguistically irrelevant constructions. The remaining categories are less frequent (the last category contains large number of various phenomena with a low frequency). Let us therefore concentrate our efforts on verbal non-projectivities in the subsequent text.
The sentences with verbal non-projectivities demonstrate that Czech is a language with a high degree of word order freedom. It is usually possible to reduce the number of non-projective constructions to zero while preserving the correctness of a sentence simply by reordering the words in the sentence. The most regular exception from this rule are sentences containing clitics.

Clitics constitute a certain fixed point in a typical Czech sentence. They are usually located on the sentence second (Wackernagel's) position and thus they are both a frequent source of non-projective constructions and an obstacle which requires special treatment when we attempt to reduce the number of non-projectivities. The situation is even more complicated because the sentence second position may contain a larger number of clitics whose mutual order is not arbitrary in some cases. Let us consider the following example (taken from [3]):

(2)	*Opravit*	*jsem*	*se*	*mu*	*to*	*včera*	*snažil*	*marně.*
	to-repair	aux-1-sg	REFL	him	it	yesterday	tried	fruitlessly

'I tried to repair it for him yesterday without success.'

In this sentence we may notice that the clitics are the main reason why the sentence is non-projective. While *jsem* 'aux-1-sg' and *se* REFL depend on the verb *snažil* 'tried', the pair of clitics *mu* 'him' and *to* 'it' depend on the infinite verb *opravit* 'to repair'. In this special case it is possible to make the sentence projective while preserving its correctness and all dependencies and morphological properties of all words by means of either swapping the two verbs and shifting the adverb slightly forward: *Snažil jsem se mu to marně včera opravit.*; or by swapping the pairs of clitics: *Opravit mu to jsem se včera snažil marně.*

[7] We would like to express our special thanks to Daniel Zeman who has provided us with the data, see also
`http://ufal.mff.cuni.cz/~zeman/projekty/neproj/index.html`

These examples actually show that our method might provide a clue for further investigation of the degree of word order freedom. The number of shifts or swaps performed in the course of the analysis by reduction with the purpose of preserving all important factors (grammatical correctness, morphological and syntactic information, dependency relations) in every step of the analysis might reflect the word order freedom of a particular language.

4.2 Evaluation

In order to obtain a deeper insight into the problem of mutual relationship between clitics, holes (non-projective constructions) and shifts necessary for the preserving a sentence correctness in the course of AR, we have chosen 100 non-projective sentences from the PDT, the portion with non-projectivity given by a modal verb (see above) and manually evaluated them. As we are concentrating primarily on the clitic / (non-)projectivity interplay here (and we want to eliminate other language phenomena) we have simplified the input sentences using AR in such a way that only words related to these phenomena are preserved. Note that discontinuous dependencies are allowed, i.e. dependent word in a position distant from its governor may be deleted.

The results of this evaluation are summarized in Tab. 1, which indicates relations between the number of clitics, the number of holes and the minimal necessary number of shifts. The table shows that although clitics are usually a primary reason why a sentence contains non-projective constructions, there surprisingly seems to be no correlation between the number of holes (number of individual non-projectivities), the number of clitics and the number of shifts. It is also quite interesting that the minimal number of necessary shifts does not exceed one regardless of the number of clitics or the number of holes.

Table 1. Sample non-projective sentences from PDT 1.0 – basic characteristics

# clitics	# sentences	# holes	# shifts	comments
0 clitics	21 / 14 / 3	1	0	main / dependent clause / question
	2	0	0	annot. error
	1	1	0	error in raw text
	1	2	1	two dependencies
1 clitic	17 / 17	1	0	main / dependent clause
	10 / 2 / 1	1	1	main / dependent clause / question
	1	2	0	main clause
	1	2	1	main clause
2 clitics	2	1	0	main clause
	6 / 1	1	1	main / dependent clause
	1	2	1	
3 clitics	1	1	0	
	1	1	1	

Table 2. Sample projective sentences from PDT 1.0 – basic characteristics

# clitics	# sentences	# holes	# shifts
1 clitic	11	0	0
	34	0	1
2 clitics	5	0	0

This observation inspired a second experiment – if the number of holes is irrelevant, how does the relationship between the number of clitics in projective sentences and the necessary number of shifts look like? The results of this experiment are presented in Tab. 2. In this case we have taken 50 randomly chosen projective sentences with clitics from the PDT and we have performed the same evaluation as in the previous experiment. The results are also quite interesting.

First, the number of clitics in projective sentences is generally lower. This supports the claim that clitics constitute one of the primary sources of non-projectivities in Czech. If the sentence contains more than two clitics, it is highly probable that it contains non-projective constructions as well.

Second, even in projective sentences it is often necessary to shift the words duringin the course of the analysis by reduction, otherwise some of the general constraints would be violated (usually the correctness preserving constraint). This actually supports the claim that neither the number of holes nor the number of clitics in a sentence correlates with the necessary number of shifts. The number of shifts indicates that clitics have rigid positions in Czech; however, the measure proposed does not sufficiently cover cases where the words with fixed positions do not enforce a shift during the reduction. Moreover, the fact that in both experiments it took maximally 1 shift to make the sentence projective in the course of the analysis by reduction indicates that this measure of word order freedom is rather too simplistic.

5 Conclusion

The results of the two experiments presented in this paper indicate that the number of shifts is an important factor providing different information than already existing measures reflecting the complexity of word order of individual sentences. However, the granularity of the proposed measure is too low and it will definitely require further refinement in the future. We plan to consider further characteristics of the delete and shift operations, esp. dis/continuous dependencies (whether dependent word is adjacent to its governing word or not) and a type of shifts (a shift of a verb / a shift across a verb).

The experiments also helped us to analyze the treebank data from a new perspective and to gain an increased insight into the phenomena responsible for higher complexity of syntactic structures of sentences of languages with higher degree of word order freedom.

Future research should aim at two important goals – to repeat the experiments with higher number of sentences (and different phenomena causing non-projectivity) and, primarily, to extend them to a different language. The comparison between languages with lower degree of word order freedom and higher number of word-order constraints and Czech would definitely bring interesting results.

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