Formal and Computational Aspects of Optimality-theoretic Syntax

Formal and Computational Aspects of Optimality-theoretic Syntax

Von der Fakultät Philosophie der Universität Stuttgart
zur Erlangung der Würde eines Doktors der
Philosophie (Dr. phil.) genehmigte Abhandlung

Vorgelegt von

Jonas Kuhn
aus Stuttgart

Hauptberichter: Prof. Dr. Christian Rohrer
Mitberichter: Dr. habil. Jürgen Wedekind
Tag der mündlichen Prüfung: 10. Mai 2001

Institut für maschinelle Sprachverarbeitung
Universität Stuttgart

2001

Universität Stuttgart
Institut für maschinelle Sprachverarbeitung
Lehrstuhl für Computerlinguistik
Azenbergstr. 12
D-70174 Stuttgart

WWW: `http://ww.ims.uni-stuttgart.de/~jonas/`
Email: `jonas@ims.uni-stuttgart.de`

Abstract

In this dissertation, I propose a formal framework for stating in detail a class of Optimality-Theoretic models for syntax. I discuss empirical consequences of the key choices in the formalization and investigate computational properties of the models, in particular decidability of the parsing and generation tasks.

The candidate analyses I assume are non-derivational, represented as tuples of parallel representation structures whose elements stand in a correspondence relation in the style of Lexical-Functional Grammar (LFG). The assumption of this type of candidates is motivated by learnability considerations and has the advantage that one can exploit formal and computational results for LFG and related grammar formalisms. The formalization I discuss (in chapter 4) builds on Joan Bresnan's original proposal of casting Optimality-Theoretic Syntax in an LFG setting (OT-LFG). The set of all possible candidates is specified by a formal LFG-style grammar; a particular candidate set is defined as those possible candidates whose functional (f-)structure is subsumed by an f-structure representing the input. OT constraints are specified as structural description schemata using the primitives of LFG. I discuss details of the status of candidates violating Faithfulness constraints, as they are required to derive expletive elements (like English *do*) and non-overt elements (like in pro-drop). I argue that in OT-LFG, Faithfulness violations can be modelled very naturally as a tension between a candidate's f-structure and its categorial structure and lexical material. Thus the subsumption-based definition of candidate sets can be kept up without implying an overly restricted candidate generation function *Gen*; in this formal model all language differences can be viewed as an effect of constraint (re-)ranking.

Besides the standard production-based (or expressive) optimization model, I discuss comprehension-based (or interpretive) optimization, in which the terminal string is fixed across the members of the candidate set (chapter 5). Formally, this is only a minor modification of the definition of the candidate set, but there are interesting conceptual and empirical issues concerning parallelism between the two "directions" of optimization, and in particular the combination of both in a bidirectional model. I present a bidirectional account of pro-drop in Italian, which derives a recoverability condition as an effect of the interaction of the two optimizations.

Building on computational results for LFG generation, I discuss the processing tasks associated with the two types of uni-directional optimization models and with their combination in a bidirectional system (chapter 6). The two main issues in processing are the control of the infinite candidate set and directionality of processing. I show that generally, the conceptually and empirically well-motivated formalization that I argue for provides a sufficiently restricted basis for a computational account. While parsing (and generation) with an unrestricted OT Syntax system is undecidable in the general case, decidability is guaranteed if either a recoverability condition based on a finite context representation is assumed, or a specific type of bidirectional model (with strong bidirectionality) is applied.

Contents

Acknowledgements

The research reported in this dissertation grew out of my work in two related projects: the B12 project (*Methods for extending, maintaining and optimizing a large grammar of German*) within the Collaborative Research Centre *Linguistic Foundations for Computational Linguistics* (SFB 340), supported by the Deutsche Forschungsgemeinschaft (DFG), and the Parallel Grammar Development Project *ParGram*, a collaborative effort of the Institut für maschinelle Sprachverarbeitung (IMS) Stuttgart, the Xerox Palo Alto Research Center (PARC), and the Xerox Research Center Europe (XRCE) Grenoble (and more recently also the University Bergen and Fuji Xerox). Parts of this dissertation are based on articles and conference papers, as indicated in the text and bibliography.

I'd like to thank all the members of the IMS for providing such an excellent working environment. In particular I wish to thank my supervisors Christian Rohrer and Jürgen Wedekind – not only for input and discussion of material related to this dissertation, but for being a source of advice and motivation over many years. Christian Rohrer has made possible several short-term stays at Xerox PARC in the context of the *ParGram* project, which provided me with invaluable input and opportunities for discussion of empirical, formal and computational issues. For all this interaction, I owe thanks to the *ParGram* people, especially Miriam Butt, Dick Crouch, Mary Dalrymple, Anette Frank, Ron Kaplan, Martin Kay, Tracy King, John Maxwell, and Annie Zaenen. Special thanks due to Anette, Tracy and John – my co-authors for (Frank et al. 1998, 2001) – for encouraging me to dig deeper into the formalization of OT-LFG, which turned out to be the starting point for this entire dissertation. Many thanks again to Jürgen for all his help with formal issues.

Extraordinary thanks go to Joan Bresnan for providing crucial input and for raising very important issues, both in our discussions during my stay in Palo Alto in spring 2000 and via email. I'd also like to thank the audience at the Stanford Syntax Workshop (March 2000) for their important feedback, as well as the audiences at the seminars in Edinburgh (July 1999) and Saarbrücken (January 2000), at the GGS conference (May 1999) and the 4th OT syntax workshop in Stuttgart (February 2001), NELS at Rutgers (October 1999), ACL 2000 in Hongkong, and the LFG 1999 conference in Manchester and the LFG/HPSG 2000 conference in Berkeley.

Thanks to Sten Vikner for initiating the lively interaction in the Stuttgart OT syntax project meetings and to the participants, especially Fabian Heck, Tanja Schmid and Ralf Vogel. I'm also indebted to Joan Bresnan, Stefanie Dipper, Arne Fitschen, Anette Frank, Ron Kaplan, and Peter Sells for comments on draft versions of this dissertation or on papers that formed the basis for some part of the dissertation. Furthermore, I've benefited from talking to many other people, including Reinhard Blutner, Mark Johnson, Frank Keller, Chris Manning, and Stefan Riezler.

I owe much to the academic teachers who initiated my interest in syntax, semantics and computational linguistics, in particular Elisabet Engdahl, Werner Frey, Hans Kamp, Uwe Reyle, Christian Rohrer, and Jürgen Wedekind.

Finally, I wish to thank my parents for their support and encouragement, and my wife Birgit for always finding ways of motivating me, even when I thought I was stuck.

Chapter 1

Introduction

This dissertation addresses the formal and computational properties of Optimality-theoretic (OT) models of grammar, in particular as they are applied in syntactic analysis. The OT approach was first introduced in the 1990s in the area of phonology (Prince and Smolensky 1993), where it was quickly adopted by a large number of researchers. Soon the framework was also applied in theoretical syntax (Legendre et al. 1993). In this area, (Grimshaw 1997) was a very influential early contribution (manuscript versions of this paper go back to 1993). The OT approach is compatible with different underlying grammatical frameworks and representations. The setting for this dissertation is the version of OT which is based on the formal framework of Lexical-Functional Grammar (LFG, Kaplan and Bresnan 1982)[1] – the OT-LFG approach, initiated by the work of Bresnan (1996, 1999, 2000, among others). The choice of a particular formalism is indispensable when the aim is to make the details of the model precise; however I will try to avoid extensive discussion of framework-internal issues. Much of the considerations expressed with the formal notions of LFG can be transferred to other formal accounts of syntax. Setting this account in the framework of LFG has the advantage that the rich literature on formal and computational aspects of this and related unification-based grammar formalisms can be exploited in the investigation of the properties of the OT model.

OT is based on the following idea: variation across the languages of the world is explained by interaction of a set of universal constraints. Such constraints say for example roughly "realize scope-bearing elements (such as *wh*-words) in a way that makes their scope visible", or "avoid realizing arguments other than in their base position". Constraints are violable and are often in mutual conflict. Depending on priorities, such conflicts can be resolved in different

[1] There are several recent introductory books for the LFG theory of syntax: (Bresnan 2001; Dalrymple 2001; Falk 2001). A collection of contributions on formal aspects of the LFG formalism is (Dalrymple et al. 1995).

ways (compare *who Ann saw* vs. *Ann saw who*). The priorities, expressed as a dominance relation or ranking between the constraints, constitute the difference between the individual languages (say, English and Chinese). From a set of competing candidate analyses, the one with the least serious constraint violations – that is, the most harmonic one – is defined as grammatical. Learning a language amounts to determining the correct dominance relation over the universal set of constraints.[2]

OT combines the formally exact approach of Generative Grammar and its detailed representations with an empirical learning approach. In a stochastic OT variant like Boersma's (1998), the learning algorithm permits in particular the derivation of frequency effects.[3] This empirical orientation brings with it the potential for resolving a longstanding and crucial problem of syntactic theory, and especially of the computational linguistics approach which attempts to benefit from the results of linguistic theory: within the classical grammatical frameworks, the extension of phenomenon-specific linguistic analyses with the goal of broader coverage on real corpus data typically hits a critical point. Beyond this point, the original generalizations have to be restricted or divided into cases in order to match the extended data basis. Formulating the relevant restrictions without causing some other analysis to be accidentally surpressed turns out to be a difficult engineering task, which the classical approach in linguistic theory has little to say about. Under the OT approach with its violable constraints and an empirical learning scheme, "training" on corpus data may lead to a finegrained and well-adjusted system of constraint interaction, which has a similar coverage as the ideal, manually tailored list of special cases. However, linguistic work stays at the level of intact generalizations, since the data tuning is performed by the learning technique, informed by frequencies of phenomena and lexical elements in the observed data.

Before such an approach can be put to use and particular strategies of corpus-based learning can be evaluated, many issues about the representation formalism and the mechanisms in the processing model have to be settled. The present dissertation is an attempt to contribute to this by proposing a non-derivational formal model of OT syntax and discussing important empirical, formal and computational properties. The focus is on issues of the architecture, i.e., how are the competing candidates determined, what candidates have to be considered, what properties of the candidates are checked? The question of what is the most adequate way of modelling priorization of the different constraints (weighting, ranking, or some stochastic variant of ranking) is to a great extent independent of the architectural issues.

[2] For an introduction to OT see (Kager 1999), which has OT phonology as its main focus, but addresses the application to syntax, too.

[3] Cf. also (Boersma and Hayes 2001). (Keller and Asudeh 2001) point out a number of problems with this particular approach; however, the general framework of a competition-based theory of syntax opens up a wide space of possibilities for modelling a competence grammar within a broader context of cognitive abilities, including performance issues.

Besides this perspective of applying a linguistically motivated competition-based model of syntax in corpus-based learning, a more immediate need of a spelled-out formalization of OT syntax and a computational account exists for ongoing linguistic work in the OT framework. To date, most work focuses on fairly restricted sets of empirical data and few selected constraints. This is in part due to the fact that OT is still a young field of study, but it seems also that there is a limit to the size of an OT analysis that can be mastered on a piece of paper. A thorough assessment of the benefits of OT presupposes computational devices that allow one to manipulate larger sets of constraints and larger candidate sets with more complex candidate analyses.

Overview

This dissertation consists of six chapters besides this introduction. Chapters 2 and 3 provide some background on OT and identify the conceptual and empirical OT-syntactic issues underlying this dissertation. Chapter 4 presents a formalization of OT syntax in the framework of LFG; chapter 5 discusses an extension of this formalization to bidirectional optimization. Chapter 6 is devoted to processing issues arising from the formalization; chapter 7 presents some conclusions and an outlook.

Chapter 2 starts with a brief introduction of the main concepts of OT, illustrated with an example from syntax. The basic explanatory mechanisms of OT are explained on the basis of simple phonological examples. This establishes the crucial role of constraint interaction in the explanation of variation across the languages of the world.

Chapter 3 moves on to conceptual and empirical issues specific to the application of OT to syntax. The two main themes of this chapter are faithfulness violations and questions of learnability. A treatment of these issues within an OT system presupposes that the formal framework in which the OT system is set have certain properties. I point out the advantages of a non-derivational setup both for candidate analyses and the OT competition system.

At the beginning of chapter 4, I give a short overview of the LFG formalism. The formalization of OT syntax builds mainly on LFG concepts (thus the framework is called OT-LFG): possible candidates are defined by an LFG-style grammar; candidate sets are defined as possible candidates whose f-structure is subsumed by the input f-structures; constraints are defined as structural description schemata using the primitives of LFG. I point out that the OT-LFG framework allows one to address the conceptual and empirical points raised in chapter 3 in an adequate way.

Chapter 5 discusses a variation of the standard production-based (or expressive) optimization model, which is straightforward on the basis of the OT-LFG formalization: comprehension-based (or interpretive) optimization, in which the terminal string is fixed across the members of the candidate set. Formally, this is only a minor modification of the definition of the candidate set, but there are interesting conceptual and empirical issues concerning parallelism between the two "directions" of optimization, and in particular the combination of both in a bidirectional model. I present a bidirectional account of pro-drop in Italian, which derives a recoverability condition as an effect of the interaction of the two optimizations.

Building on computational results for LFG generation, chapter 6 discusses the processing tasks associated with the two types of uni-directional optimization models and with the various combinations in a bidirectional system (chapter 6). The two main issues in processing are the control of the infinite candidate set and directionality of processing. I show that generally, the conceptually and empirically well-motivated formalization of chapters 4 and 5 provides a sufficiently restricted basis for a computational account. While parsing (and generation) with an unrestricted OT Syntax system is undecidable in the general case, decidability is guaranteed if either a recoverability condition based on a finite context representation is assumed, or a specific type of bidirectional model (with strong bidirectionality) is applied.

Chapter 7 constitutes a conclusion of the dissertation with a summary of the main results and a discussion of open points and directions for future research.

Chapter 2

The foundations of OT

This chapter introduces the general ideas of the Optimality-theoretic approach in linguistics. Optimality Theory (OT) was first developed for phonology by Prince and Smolensky (1993), and has quickly attracted many researchers in phonology, but also morphology, syntax, semantics and pragmatics. This dissertation is mainly focused on Optimality-theoretic syntax, so the first illustration of constraint interaction in sec. 2.1 is drawn from this area. Nevertheless, it is helpful to introduce the basic explanatory devices with phonological examples, as will be done in sec. 2.2.

2.1 Conflicting violable constraints

This section presents an illustrative example of an analysis in OT syntax. It is taken from Grimshaw's (1997) account of inversion in English, which is set in a syntactic framework working with a representational simulation of movement derivations in the style of *Government-and-Binding* theory (GB).[1] Grimshaw's paper was probably the most influential early work applying OT methods to syntactic phenomena. It presents a very elegant analysis for the notorious auxiliary/inversion facts of English. This paper has prompted many researchers' interest in OT syntax. Bresnan (2000, sec. 2) shows that Grimshaw's constraint system can be reconstructed in the LFG framework (see chapter 4), and many of the examples I use to illustrate the formalizations in this dissertation will also be based on this fragment. Here, I will just go through a simplified analysis to informally introduce the basic concepts of OT syntax.

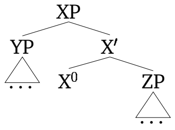
The miniature fragment I will use for illustration is based on the syntactic OT constraints constraints in (2.1) (Grimshaw 1997, 374).

[1] Cf. (Chomsky 1981); for in introduction, see e.g. (Haegeman 1994).

(2.1) Op-Spec Syntactic operators must be in specifier position.
Ob-Hd (Obligatory Head) A projection has a head.
Stay Trace is not allowed.

Note that the constraints are formulated as conditions on syntactic representations, in this case tree configurations following the GB tradition (in particular assuming *traces* marking the base position of elements that have been *moved* to a different position at the level of surface structure). The concepts of head, projection and specifier are standard terms from *X-bar theory*, referring to particular positions in the *X-bar scheme* (2.2), which underlies all well-formed syntactic trees. The relevant *syntactic operators* (as referred to in the Op-Spec constraint) for our present purposes are *wh*-phrases like *who* or *what*.

(2.2)



X^0: head
X′, XP: projections of X^0
ZP: complement of X^0
YP: specifier to XP

In general, it is not possible to satisfy all OT constraints at the same time since some of them are in mutual conflict. For example according to the underlying assumptions about representations, some syntactic operators cannot be base-generated in specifier position. So, in order to satisfy Op-Spec such operators have to be moved to this position, which inevitably gives rise to a trace violating Stay. It is a key assumption of OT that it is legitimate for a well-formed analysis to violate certain constraints (in order to satisfy some other constraints). Thus, contrary to the principles and constraints of pre-OT frameworks of generative linguistics, OT constraints are *violable*.

By hypothesis the set of constraints is universal, but what differs from language to language is the importance of the individual constraints. In some languages it is more important to satisfy Op-Spec than Stay, in other languages vice versa. This is captured by assuming a language-specific hierarchical dominance ranking of the constraints. The dominance relation is written as $\gg$ ('is more highly ranked than'). For English, the dominance ranking for our three constraints is as follows: Op-Spec $\gg$ Ob-Hd $\gg$ Stay.

The type of relation between constraints assumed in standard OT approaches is one of *strict dominance*, meaning that higher-ranking constraints take absolute priority over lower-ranking constraints: if an analysis satisfies a higher-ranking constraint better than any alternative analysis, it does not matter how many violations of lower-ranking constraints the analysis incurs.

The assumption of conflicting violable constraints comes with an inherent need to make comparisons in order to determine what is the well-formed, or grammatical, analysis. This is captured by the abstract process of harmony evaluation – called *Eval* – in which a set of candidate analyses or competitors is evaluated according to the language-particular constraint ranking. In a pairwise comparison, the most *harmonic* candidate (the "winner") is determined. Harmony is defined as follows.

(2.3) A_1 is more harmonic than A_2 ($A_1 \succ A_2$) if it contains fewer violations for the highest-ranking constraint in which the marking of A_1 and A_2 differs.

We can subdivide the evaluation process in

- a first step identifying the constraint violations (this is sometimes modelled by a function *marks* from candidates to multisets or bags of constraint violation marks), and
- a second step actually determining the harmony of the candidates.

Only the latter step is language-dependent. When there is no risk of confusion, I will sometimes also call this narrower second step harmony evaluation or *Eval*.

Before looking at an example of harmony evaluation at work, we have to know what candidates enter the competition for the most harmonic candidate. This is a very crucial question, since obviously the result of the comparison may vary significantly depending on how "hard" the competition is. Intuitively, only genuine *alternatives* should be compared. That means that all candidates should be equivalent in terms of their communicative force. Here, OT accounts are not always very explicit, but it is a widespread assumption that all competing candidates share the same semantic content.[2] If we assume some representation of the semantic content, candidate sets can then be defined by a function that maps a content representation to the set of all analyses expressing this content. This function is called *Gen* (for candidate generation), and since it is tempting to think of this abstract function as some derivational process, the content representation that *Gen* takes as an argument is typically called the *input*. I will follow this standard terminology without implying that *Gen* is indeed a derivational process.[3]

[2] The issue will be discussed in sec. 3.3.3.
[3] Compare the discussion in sec. 3.3.5.

Strictly, in the GB-based model the input should be the LF (logical form), possibly paired with d-structure, but for the purposes of Grimshaw's fragment it suffices to assume an input consisting of "a lexical head plus its argument structure and an assignment of lexical heads to its arguments, plus a specification of the associated tense and aspect" (Grimshaw 1997, 376). Given a particular such input I, *Gen*(I) is the set of all candidate analyses with I as the underlying argument structure etc. Note that the definition of *Gen* incorporates certain inviolable principles of what counts as a valid candidate. In the present fragment this comprises the principles of X-bar theory and some principles on chain formation (for representing the movement operations).

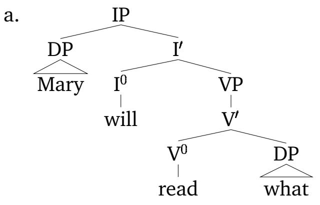
So, we can now specify the input for an example (Grimshaw 1997, 378): (2.4); the first column of table in (2.5) shows some sample candidates that are contained in the set that *Gen* assigns to this input.[4] In (2.6), the full tree structures for the three candidates are given, with the movement transformations illustrated by arrows.

(2.4) read(x, y)
$x =$ Mary
$y =$ what
tense = future

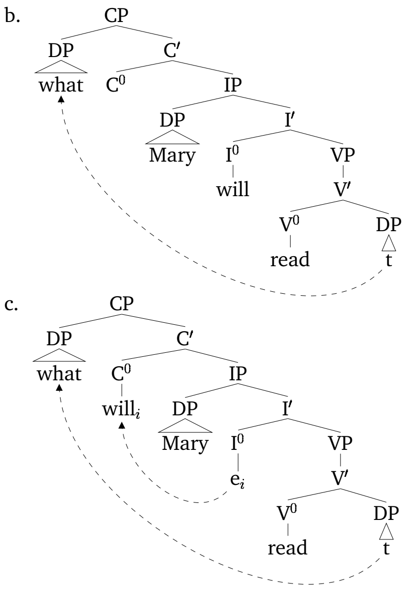
(2.5)

Candidates	Constraint violations
a. $[_{\text{IP}}$ Mary will $[_{\text{VP}}$ read what$]]$	*OP-SPEC
b. $[_{\text{CP}}$ what **e** $[_{\text{IP}}$ Mary will $[_{\text{VP}}$ read t$]]]$	*OB-HD, *STAY
c. $[_{\text{CP}}$ what **will**$_i$ $[_{\text{IP}}$ Mary **e**$_i$ $[_{\text{VP}}$ read t$]]]$	*STAY, *STAY

(2.6)



[4] In this example, I follow Grimshaw's GB-style notation: 't' marks the trace of the moved *wh*-word *what*; '**e**' marks an empty head (of the CP projection); '**will**$_i$ – **e**$_i$' is the chain of *will*'s head movement from I to C. (Note that **e**$_i$ is a trace, while **e** is not.)



For each candidate, the function *marks* checks which of the constraints it satisfies; a violation is marked in the second column of (2.5), with an '*' preceding the constraint name. Candidate a. has the *wh*-operator *what* in the complement position of the verb, thus failing to satisfy the constraint OP-SPEC in (2.1). In candidate b., the CP doesn't contain a head, leading to a OB-HD violation; furthermore, *what* has been moved to the specifier of CP (so it avoids a OP-SPEC violation), leaving behind a trace and thus violating STAY once. Candidate c. avoids the empty C^0 by moving the auxiliary *will* from I^0 into this position – at the cost of incurring an additional STAY violation. So we see that the constraint conflict triggered by the presence of a *wh*-operator in the input is resolved in different ways in each of the candidates.

Based on this marking of constraint violations for all analyses in the candidate set, and the language-specific constraint hierarchy, now the function *Eval* determines the most harmonic, or optimal, candidate: by definition, this is the only grammatical analysis for the underlying input representation. (There may also be a set of equally harmonic candidates.) The standard notation for the result of the evaluation is a *tableau* (2.7), with the columns for the constraint reflecting the hierarchy of the language under consideration. It is customary to list the input in the top left-hand table cell.

(2.7)

Input: read(x, y), x = Mary, y = what, tense = future		Op-Spec	Ob-Hd	Stay
a.	[$_{\text{IP}}$ Mary will [$_{\text{VP}}$ read what]]	*!		
b.	[$_{\text{CP}}$ what **e** [$_{\text{IP}}$ Mary will [$_{\text{VP}}$ read t]]]		*!	*
c. ☞	[$_{\text{CP}}$ what **will**$_i$ [$_{\text{IP}}$ Mary **e**$_i$ [$_{\text{VP}}$ read t]]]			**

If a candidate loses in a pairwise comparison, the “fatal” mark is highlighted with an ‘!’ (e.g., candidate a. is less harmonic than b., since they differ in the highest-ranked constraint Op-Spec). Note that the score that the losing candidate has for lower-ranked constraints is completely irrelevant. Ultimately, the candidate that remains without a fatal constraint violation is marked with the symbol ☞ as the winner of the entire competition. In the example, candidate c. is optimal, although it violates the constraint Stay twice. The other analyses are predicted to be ungrammatical. Different languages are characterized by different relative rankings of the constraints. For instance, a language with *wh* in situ may rank Op-Spec lower than Stay, which will cause candidate a. in (2.7), to be the winner. Note that there will always be at least one winning analysis for a given (nonempty) candidate set, since optimality is defined relative to the competitors.[5]

After this informal example, we can identify the notions that a formalization of OT must pinpoint: the input representation, the function *Gen*, the formulation of constraints, and harmony evaluation (*Eval*), consisting of the function *marks* checking for constraint violations, and the determination of harmony based on the language-specific constraint ranking. For some of these concepts, the assumptions made in different incarnations of OT vary significantly.

In chapter 4, I will address the LFG-based approach to formalization of OT Syntax (following work by Bresnan – 1996, 2000), which assumes strictly nonderivational candidate analyses. All relevant aspects of the candidates can be encoded representationally, so there is good reason to opt for the conceptually simpler choice of comparing static objects, in particular since the mathematical and computational properties of LFG-like formalisms have been studied extensively.[6]

In the remainder of this chapter and in the following chapter 3, I will discuss some of the assumptions, techniques and methodological principles adopted in the Optimality-theoretic approach in linguistics.

[5] This means that the phenomenon of language-particular ineffability cannot be modelled in the standard OT model. This will be discussed in sec. 3.3.3.

[6] Compare also the discussion in sec. 3.3.5.

2.2 Factorial typology and the grounding of constraints

One of the main arguments for the OT approach is its ability to make typological predictions. Since this dissertation is mainly about formal and computational aspects of syntactic OT systems, this empirical aspect is not a central topic in the later chapters. However, when one wants to decide between several different, but related architectures it is important to be aware of the aspects that motivate the linguistic application of optimization in the first place. Therefore I will review the structure of a factorial typology argument (based on the example from Kager 1999, sec. 1.7).

Using phonological data for this purpose has not only the advantage of keeping the analyses we have to look at simple, but is also a good starting point for a discussion of the *grounding* of constraints – an issue which is interweaved with the explanatory role of factorial typology.

2.2.1 Factorial typology

Under different dominance rankings over a set of constraints, different analyses in a candidate set come out as the winner. Since by definition, only the winners are in the language described by the OT system, changing the constraint ranking gives us different languages. But with reranking over a fixed set of constraints we do not get *arbitrary* collections of winners (i.e., languages) – the choice of constraints (plus the OT assumptions) enforces certain patterns. This is what factorial typology is about.

Using the illustrative example of (Kager 1999, sec. 1.7), let us look at nasality of vowels in closed syllables. The phonological analysis is supposed to predict under what conditions vowels are pronounced nasally or not nasally. So in the candidate set both the possibility of keeping the underlying nasality and a change of the underlying nasality have to be provided. Such potential changes of underlying information are controlled by *faithfulness constraints*, which favour candidates without such changes. Typically, faithfulness constraints are in conflict with *markedness constraints*, which favour certain properties of the output form independent of what the underlying form is like. (Faithfulness constraints are discussed in more detail in sec. 3.2.)

For the present illustrative purpose, we are only interested in whether or not a nasal vowel in the input will also be realized as a nasal in the winning candidate, potentially depending on the following consonant. For this consonant, again, it only matters whether it is a (tautosyllabic) nasal, like [n], or not. So, it suffices to look at the following four underlying word forms as representatives for the phenomenon we are interested in: /pan/, /pãn/, /pal/, /pãl/. The input /pan/ can be either realized faithfully as [pan], or, violating faithfulness, as [pãn] (we are not considering faithfulness violations in the realization of the consonant). /pãn/ could come out as [pãn] or [pan]. Likewise for the other words. So, combinatorially, there are 16 different ways natural languages could behave, as shown in (2.8) Alternative (2.8a) is faithful in all cases, alternative (2.8p) is "unfaithful" in all cases. In between, we have any possible combination of faithfulness in some of the cases, with unfaithfulness in the other cases.

(2.8) a. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pãl]}
b. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pãl]}
c. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pãl]}
d. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pãl]}
e. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pal]}
f. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pãl]}
g. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pãl]}
h. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pal]}
i. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pãl]}
j. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pal]}
k. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pal]}
l. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pãl]}
m. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pal]}
n. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pal]}
o. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pal]}
p. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pal]}

Let us now look at a linguistically sensible OT analysis of the data (the motivation for picking a particular set of constraints will be discussed further down). We have already talked about faithfulness, so a faithfulness constraint is an important participant in the constraint interaction. The relevant constraint is:[7]

[7] The input-output identity constraint IDENT-IO is part of the Correspondence Theory approach of (McCarthy and Prince 1995).

(2.9) IDENT-IO(nasal)
The specification of the feature [nasal] of an input segment must be preserved in its output correspondent.

Furthermore, we have the following markedness constraints:

(2.10) *V$_{\text{NASAL}}$
Vowels must not be nasal.

(2.11) *V$_{\text{ORAL}}$N
Before a tautosyllabic nasal, vowels must not be oral.

(2.10) is a context-free markedness constraint. If it is not dominated by any other constraints, the language will not contain any nasal vowels at all. (2.11) is a context-sensitive markedness constraint. Given these three constraints, there are 6 possible rankings (in general for a set of n constraints, there are $n!$ possible rankings, thus the term *factorial* typology):

(2.12) a. IDENT-IO(nasal) $\gg$ *V$_{\text{NASAL}}$ $\gg$ *V$_{\text{ORAL}}$N
b. IDENT-IO(nasal) $\gg$ *V$_{\text{ORAL}}$N $\gg$ *V$_{\text{NASAL}}$
c. *V$_{\text{ORAL}}$N $\gg$ IDENT-IO(nasal) $\gg$ *V$_{\text{NASAL}}$
d. *V$_{\text{ORAL}}$N $\gg$ *V$_{\text{NASAL}}$ $\gg$ IDENT-IO(nasal)
e. *V$_{\text{NASAL}}$ $\gg$ *V$_{\text{ORAL}}$N $\gg$ IDENT-IO(nasal)
f. *V$_{\text{NASAL}}$ $\gg$ IDENT-IO(nasal) $\gg$ *V$_{\text{ORAL}}$N

With ranking (2.12a), we get the competitions in (2.13). Since Faithfulness (IDENT-IO(nasal)) is undominated, the unfaithful candidate loses in all four cases (note the exclamation marks in the first column of each small tableau). So we get a language that displays full contrast in the output forms. Typologically, this is a widespread pattern. Note that the relative ranking of the two markedness constraints plays no role (given the set of data), so the outcome with ranking (2.12b) is identical. The ranking *V$_{\text{NASAL}}$ $\gg$ *V$_{\text{ORAL}}$N is said not to be *crucial* – in this situation it is common in the literature that the dominance relation is left unspecified for the two constraints: The hierarchy IDENT-IO(nasal) $\gg$ { *V$_{\text{NASAL}}$, *V$_{\text{ORAL}}$N } specifies all crucial rankings.[8]

[8] Often, the dominance ranking is formally defined as a total relation, so effectively for the non-crucial rankings one or the other alternative will actually hold. But for the cases under discussion, this does not have an effect on the outcome.

(2.13) *Full contrast*
Ident-IO(nasal) ≫ $*V_{\text{NASAL}}$ ≫ $*V_{\text{ORAL}}N$

(i) Input: /pan/			Id-IO(nasal)	$*V_{\text{NASAL}}$	$*V_{\text{ORAL}}N$
a.		[pãn]	*!	*	
b.	☞	[pan]			*

(ii) Input: /pãn/			Id-IO(nasal)	$*V_{\text{NASAL}}$	$*V_{\text{ORAL}}N$
a.	☞	[pãn]		*	
b.		[pan]	*!		*

(iii) Input: /pal/			Id-IO(nasal)	$*V_{\text{NASAL}}$	$*V_{\text{ORAL}}N$
a.		[pãl]	*!	*	
b.	☞	[pal]			*

(iv) Input: /pãl/			Id-IO(nasal)	$*V_{\text{NASAL}}$	$*V_{\text{ORAL}}N$
a.	☞	[pãl]		*	
b.		[pal]	*!		*

If we look at ranking (2.12c), we get the competitions in (2.14):

(2.14) *Positional neutralization*
$*V_{\text{ORAL}}N$ ≫ Ident-IO(nasal) ≫ $*V_{\text{NASAL}}$

(i) Input: /pan/			$*V_{\text{ORAL}}N$	Id-IO(nasal)	$*V_{\text{NASAL}}$
a.	☞	[pãn]		*	*
b.		[pan]	*!		

(ii) Input: /pãn/			$*V_{\text{ORAL}}N$	Id-IO(nasal)	$*V_{\text{NASAL}}$
a.	☞	[pãn]			*
b.		[pan]	*!	*	

(iii) Input: /pal/			$*V_{\text{ORAL}}N$	Id-IO(nasal)	$*V_{\text{NASAL}}$
a.		[pãl]		*!	*
b.	☞	[pal]			

(iv) Input: /pãl/			$*V_{\text{ORAL}}N$	Id-IO(nasal)	$*V_{\text{NASAL}}$
a.	☞	[pãl]			*
b.		[pal]		*!	

Here, the context-sensitive markedness constraint $*V_{\text{ORAL}}N$ outranks faithfulness (Ident-IO(nasal)). This means for the context in which the condition of $*V_{\text{ORAL}}N$ fires (i.e., (i) and (ii) where we have a nasal consonant), it is more important to satisfy this markedness constraint than to be faithful to the input. Thus in the (i) case, we get an unfaithful output, realizing an underlying oral vowel as a nasal. The (iii) and (iv) cases are unaffected, since faithfulness jumps in to level out the effect that $*V_{\text{NASAL}}$ could have. This phenomenon is called *positional neutralization*. For certain contexts (i.e., in certain positions), differences in the underlying forms are neutralized: before /n/, both an underlying /a/ and an /ã/ come out the same.

Based on the hierarchy (2.12d) harmony evaluation yields (2.15) as a result. With the context-sensitive markedness constraint highest-ranking, followed by the context-free markedness constraints, and faithfulness ranked lowest, we get the same effect as before for the nasal context ((i) and (ii)), plus we get the effect of $*V_{\text{NASAL}}$ for the non-nasal context (case (iii) and (iv)). So we observe *allophonic variation*. In both contexts, neutrlization of underlying differences occurs. Two of the four cases ((i) and (iv)) display unfaithfulness of the output. This behaviour is found in many dialects of English where vowels before nasal consonants (like in *sand, meant*) are nasalized.

(2.15) *Allophonic variation*
$*V_{\text{ORAL}}N$ ≫ $*V_{\text{NASAL}}$ ≫ Ident-IO(nasal)

(i) Input: /pan/			$*V_{\text{ORAL}}N$	$*V_{\text{NASAL}}$	Id-IO(nasal)
a.	☞	[pãn]		*	*
b.		[pan]	*!		

(ii) Input: /pãn/			$*V_{\text{ORAL}}N$	$*V_{\text{NASAL}}$	Id-IO(nasal)
a.	☞	[pãn]		*	
b.		[pan]	*!		*

(iii) Input: /pal/			$*V_{\text{ORAL}}N$	$*V_{\text{NASAL}}$	Id-IO(nasal)
a.		[pãl]		*!	*
b.	☞	[pal]			

(iv) Input: /pãl/			$*V_{\text{ORAL}}N$	$*V_{\text{NASAL}}$	Id-IO(nasal)
a.		[pãl]		*!	
b.	☞	[pal]			*

The neutralization caused by the low ranking of faithfulness in allophonic variation languages leads to a somewhat peculiar situation: if one looks at the output (the winning candidates) only, the (i) and the (ii) case are indistinguishable, and so are (iii) and (iv). So there is no context where one could see what the nasality of the actually underlying vowel is. Hence, a learner of this language could never find a clue to distiguish the alternative underlying forms, so it is sufficient to store only one of them in the inventory of underlying lexical forms. The question which one is picked in learning is addressed in OT by Lexicon Optimization.[9]

As the final ranking options, let us look at (2.12e) as representative for both (2.12e) and (2.12f), since the highest-ranking constraint alone is decisive. The tableaux in (2.16) result. We again get unfaithfulness in two out of four cases ((ii) and (iv)), where in this case the global markedness of nasal vowels suppresses all other factors – be it the context-sensitive markedness of the alternative oral vowel or faithfulness to the underlying input form. So, in this language vowels are never nasal, there is a *lack of variation* for the nasality feature on vowels. Typologically, this kind of behaviour is attested for different features in many languages. Our concrete case here – lack of nasality for vowels – actually holds for the majority of languages of the world. Note that as in the previous case, from the output it is impossible to tell whether the underlying input form had a nasal vowel or not. So again, Lexicon Optimization will apply in learning.

(2.16) *Lack of variation*

*V$_{\text{NASAL}}$ $\gg$ *V$_{\text{ORAL}}$N $\gg$ IDENT-IO(nasal)

(i) Input: /pan/	*V$_{\text{NASAL}}$	*V$_{\text{ORAL}}$N	ID-IO(nasal)
a. [pãn]	*!		
b. ☞ [pan]		*	

(ii) Input: /pãn/	*V$_{\text{NASAL}}$	*V$_{\text{ORAL}}$N	ID-IO(nasal)
a. [pãn]	*!		
b. ☞ [pan]		*	*

(iii) Input: /pal/	*V$_{\text{NASAL}}$	*V$_{\text{ORAL}}$N	ID-IO(nasal)
a. [pãl]	*!		
b. ☞ [pal]			

(iv) Input: /pãl/	*V$_{\text{NASAL}}$	*V$_{\text{ORAL}}$N	ID-IO(nasal)
a. [pãl]	*!		
b. ☞ [pal]			*

[9] Compare (Kager 1999, sec. 1.6; 7.5.3). Lexicon Optimization is an instance of bidirectional optimization, which is addressed in chapter 5 of this dissertation.

2.2.2 The predictive power of factorial typology

We have seen all six possible rankings for the three constraints under consideration – with four empirically distinguishable outcomes. Recall that in (2.8), 16 logically possible language behaviours were observed, of which now only four are predicted: the alternatives a., b., h., and j, repeated below.

(2.8) *Possible languages*

a. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pãl]}
b. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pãl]}
h. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pal]}
j. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pal]}

With the three constraints (2.9), (2.10) and (2.11), no other language behaviour can be derived. If we look at the other logical possibilities, this turns out to be a desirable result: in the languages of the world, only the predicted patterns can be found. Nasal vowels are universally more marked than oral vowels. There are many languages without nasal vowels, but none without oral vowels (as in (2.8g)). For nasal vowels the position before non-nasal consonants is again universally more marked than the position before nasal consonants. This excludes a language like (2.8c), in which the nasality of the vowel is neutralized to an oral vowel before /n/ but not before /l/.

(2.8) *Impossible languages*

c. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pãl]}
d. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pãl]}
e. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pal]}
f. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pãl]}
g. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pãl]}
i. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pãl]}
k. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pal]}
l. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pãl]}
m. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pal]}
n. {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pãl], /pãl/ → [pal]}
o. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pal]}
p. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pal]}

As should be clear by now, the three constraints for the linguistic OT analysis were intentionally chosen to reflect the typological pattern in the languages of the world. This set-up demonstrates the workings of the explanatory machinery of the Optimality-theoretic approach: With a small set of constraints, the space of logically possible formal languages is reduced to a smaller spectrum, which serves as OT's model for the possible natural languages.

Thus, apart from Occam's razor, which will favour a system with a small number of constraints, the following two criteria for the adequacy of an OT system can be identified:

(2.17) *Criteria for the adequacy of an OT system*

a. The typologically attested spectrum of languages should be correctly predicted by the factorial typology of the constraints assumed.

b. The constraints used should have an independent motivation.

I will first illustrate a situation where an attempt of an OT analysis fails to satisfy criterion (2.17a). Assume a set of three hypothetical constraints:

(2.18) *Hypothetical constraints*

a. Ident-IO(nasal = +)
If an input segment is specified as [nasal = +], this must be preserved in its output correspondent.

b. $V_{NASAL=\alpha}C_{NASAL=\alpha}$
The nasality features in a vowel and a following consonant are identical.

c. *V_{NASAL}N
Before a tautosyllabic nasal, vowels must not be nasal.

(2.18a) is a more focused (i.e., weaker) variant of the faithfulness constraint (2.9) Ident-IO(nasal). It only demands that underlying nasals are rendered faithfully. If we have /pan/ → [pãn], this constraint is not violated. (2.18b) is a stronger variant of (2.11) *V_{ORAL}N, punishing also the situation of a nasal vowel preceding a non-nasal consonant (as in [pãl]). (2.18c) is a new contextual markedness constraint. We may think that these are the correct constraints for modelling nasality of vowels in the languages of the world. As the tableaux in (2.19) show, the ranking Ident-IO(nasal = +) ≫ $V_{NASAL=\alpha}C_{NASAL=\alpha}$ ≫ *V_{NASAL}N gives us the positional neutralization language (2.8b).

(2.19) *Positional neutralization* (*with hypothetical constraint set*)
Ident-IO(nasal = +) ≫ $V_{NASAL=\alpha}C_{NASAL=\alpha}$ ≫ *V_{NASAL}N

(i) Input: /pan/	Id-IO(nas = +)	$V_{NAS=\alpha}C_{NAS=\alpha}$	*V_{NASAL}N
a. ☞ [pãn]			*
b. [pan]		*!	

(ii) Input: /pãn/	Id-IO(nas = +)	$V_{NAS=\alpha}C_{NAS=\alpha}$	*V_{NASAL}N
a. ☞ [pãn]			*
b. [pan]	*!	*	

(iii) Input: /pal/	Id-IO(nas = +)	$V_{NAS=\alpha}C_{NAS=\alpha}$	*V_{NASAL}N
a. [pãl]		*!	*
b. ☞ [pal]			

(iv) Input: /pãl/	Id-IO(nas = +)	$V_{NAS=\alpha}C_{NAS=\alpha}$	*V_{NASAL}N
a. ☞ [pãl]		*	
b. [pal]	*!		

With the ranking Ident-IO(nasal = +) ≫ *V_{NASAL}N ≫ $V_{NASAL=\alpha}C_{NASAL=\alpha}$ (reversing the two lower constraints), all cases apart from (i) are the same. So we would get the free-variation language (2.8a). With $V_{NASAL=\alpha}C_{NASAL=\alpha}$ highest-ranking, it is easy to see that independent of the relative ranking of the other two constraints, we will always get the pattern {/pan/ → [pãn], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pal]}, i.e., the allphonic-variation language (2.8h). Lastly, we might argue that the ranking *V_{NASAL}N ≫ $V_{NASAL=\alpha}C_{NASAL=\alpha}$ ≫ Ident-IO(nasal = +) gives us the fourth language with lack of variation: (2.20) on page 20.

The problem is however that we have not yet looked at the complete factorial typology! There is still the ranking which is like the previous one, but with the lower two constraints swapped: *V_{NASAL}N ≫ Ident-IO(nasal = +) ≫ $V_{NASAL=\alpha}C_{NASAL=\alpha}$. For (iv), this ranking *does* make a difference, so unlike the original constraint set, the hypothetical constraint set wrongly predicts a fifth possible language:

(2.8) c. {/pan/ → [pan], /pãn/ → [pan], /pal/ → [pal], /pãl/ → [pãl]}

(2.20) *Lack of variation* (*with hypothetical constraint set*)
$*\mathrm{V}_{\text{NASAL}}\mathrm{N} \gg \mathrm{V}_{\text{NASAL}=\alpha}\mathrm{C}_{\text{NASAL}=\alpha} \gg$ IDENT-IO(NASAL = +)

(i) Input: /pan/	$*\mathrm{V}_{\text{NASAL}}\mathrm{N}$	$\mathrm{V}_{\text{NAS}=\alpha}\mathrm{C}_{\text{NAS}=\alpha}$	ID-IO(NAS = +)
a. [pãn]	*!		
b. ☞ [pan]		*	

(ii) Input: /pãn/	$*\mathrm{V}_{\text{NASAL}}\mathrm{N}$	$\mathrm{V}_{\text{NAS}=\alpha}\mathrm{C}_{\text{NAS}=\alpha}$	ID-IO(NAS = +)
a. [pãn]	*!	*	
b. ☞ [pan]			*

(iii) Input: /pal/	$*\mathrm{V}_{\text{NASAL}}\mathrm{N}$	$\mathrm{V}_{\text{NAS}=\alpha}\mathrm{C}_{\text{NAS}=\alpha}$	ID-IO(NAS = +)
a. [pãl]		*!	
b. ☞ [pal]			

(iv) Input: /pãl/	$*\mathrm{V}_{\text{NASAL}}\mathrm{N}$	$\mathrm{V}_{\text{NAS}=\alpha}\mathrm{C}_{\text{NAS}=\alpha}$	ID-IO(NAS = +)
a. [pãl]		*!	
b. ☞ [pal]			*

This demonstrates the workings of criterion (2.17a), which demands that the factorial typology formally predicted has to be checked at the empirically observed typology.

2.2.3 The grounding of constraints

Besides the typological criterion (2.17a) for the adequacy of an OT constraint set, we have criterion (2.17b), demanding independent motivation for the constraints.

In phonological OT, phonetic circumstances can often give a very clear indication of what segments are marked or what combination of segments is marked. Such evidence can originate from properties of either articulation or perception, and it provides *phonetic grounding* of a constraint. Let us go through the original three constraints (2.9) IDENT-IO(nasal), (2.10) $*\mathrm{V}_{\text{NASAL}}$ and (2.11) $*\mathrm{V}_{\text{ORAL}}\mathrm{N}$, starting with the last one. Without going into much articulatory detail, it is plausible that the sequence of an oral vowel and a (tautosyllabic) nasal consonant requires more effort (lowering the velum to allow airflow through the nose) than that of a nasal vowel and a nasal consonant. This provides phonetic grounding for constraint (2.11) $*\mathrm{V}_{\text{ORAL}}\mathrm{N}$. Note that the constraint $*\mathrm{V}_{\text{NASAL}}\mathrm{N}$ from the hypothetical constraint set (2.18) lacks such a motivation.

For faithfulness constraints like (2.9) IDENT-IO(nasal), the grounding issue does not pose itself in the same way, since we can never *observe* the underlying forms directly; their shape is a theoretical construct that we can define as adequate. What is important is that we use them in a consistent way. Formally, it is conceivable to assume the mirror-image of the IDENT-IO constraint (something like *IDENT-IO or DIFF-IO, if we have binary valued features), which would mean that a free-variation language would be modelled as (2.8p) rather than (2.8a).

(2.8) a. {/pan/ → [pan], /pãn/ → [pãn], /pal/ → [pal], /pãl/ → [pãl]}
p. {/pan/ → [pãn], /pãn/ → [pan], /pal/ → [pãl], /pãl/ → [pal]}

We would no longer have four faithful instances, but rather what looks like four unfaithful instances (defined as the unmarked case in this thought experiment).[10] However, it would not be very helpful to name the underlying forms in this confusing way.

Let us look at the phonetic grounding of the other markedness constraint, (2.10) $*\mathrm{V}_{\text{NASAL}}$. Here, the situation may already be a little less obvious than it was for $*\mathrm{V}_{\text{ORAL}}\mathrm{N}$: Why should nasal vowels be more marked a priori (taking into account that ability to close off the nasal cavity has evolved only quite recently in terms of evolution of the *homo sapiens*)? An indirect functional motivation may recur on perceptual factors: in order to exploit the space of different vowel qualities ([a] vs. [u] vs. [i], etc.) in a maximally effective way, the perceived vowel qualities should be maximally distinct – and indeed the difference between oral vowels can be perceived more clearly than the difference between nasal vowels. Thus, using oral vowels is more efficient from a functional perspective, which motivates a constraint $*\mathrm{V}_{\text{NASAL}}$.

As the example shows, criteria (2.17a) and (2.17b) will typically interact in finding a suitable set of candidates – the typological observation that many languages lack nasal vowels, while all languages have oral vowels is so striking that it may give sufficient indication for postulating a constraint $*\mathrm{V}_{\text{NASAL}}$. Based on this example, one might think that the typological predictions alone may suffice to characterize an appropriate constraint system. However the following example will show that the constraints one postulates should indeed also be evaluated according to criterion (2.17b) – independent motivation. Assume another hypothetical set of constraints:

[10] As one can check, the typological data would be easily derivable with this upside-down system; (2.8n) would replace (2.8b); the neutralization paradigms (2.8h) and (2.8j) would stay the same.

(2.21) *Hypothetical constraints*

a. *V$_{\text{NASAL}}$

b. V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$

c. EXISTFAITHFUL-V$_{\text{NASAL}}$
The output must contain a faithful nasal vowel.

Constraint (2.21a) is the known constraint disfavouring nasal vowels (2.10). (2.21b) is the same constraint as (2.18b) in the previous hypothetical constraint set. It demands that the value of the nasality features on a vowel-consonant combination be identical and is thus violated by the forms [pan] and [pãl]. Note that this constraint is not at all implausible. Now, if we also assume constraint (2.21c) (for which we do not have any independent motivation), the striking result is that we can derive exactly the same set of languages as with the constraints (2.9), (2.10) and (2.11) from above: Constraint (2.21c) is violated by both /pan/ → [pan] and /pan/ → [pãn] (neither of them contains a *faithful* nasal vowel, since the underlying form does not contain one); furthermore it is violated by the unfaithful candidate /pãn/ → [pan]. With the /pal/ and /pãn/ competitions, the situation is parallel.

With V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$ (2.21b) ranked the highest, we get language (2.8h) (with [pãn] and [pal] as the only overt forms), no matter how the other two constraints are ranked. With *V$_{\text{NASAL}}$ (2.21a) ranked the highest, we always get (2.8j) (as in (2.16)). With the ranking EXISTFAITHFUL-V$_{\text{NASAL}}$ ≫ *V$_{\text{NASAL}}$ ≫ V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$, we get (2.8a), with EXISTFAITHFUL-V$_{\text{NASAL}}$ ≫ V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$ ≫ *V$_{\text{NASAL}}$, the resulting language is (2.8b). The last result is illustrated in (2.22) on page 23.

This hypothetical example shows that just having a minimal set of constraints which predicts the typological data correctly does not guarantee that the most adequate constraint set has already been found. (2.21c) EXISTFAITHFUL-V$_{\text{NASAL}}$ is hard to motivate as a primitive constraint. So, if we take into account criterion (2.17b), the original set of constraints turns out superior.

(2.22) *Positional neutralization* (*with hypothetical constraint set*)
EXISTFAITHFUL-V$_{\text{NASAL}}$ ≫ V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$ ≫ *V$_{\text{NASAL}}$

(i) Input: /pan/	EXFAITH-V$_{\text{NASAL}}$	V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$	*V$_{\text{NASAL}}$
a. ☞ [pãn]	*		*
b. [pan]	*	*!	

(ii) Input: /pãn/	EXFAITH-V$_{\text{NASAL}}$	V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$	*V$_{\text{NASAL}}$
a. ☞ [pãn]			*
b. [pan]	*!	*	

(iii) Input: /pal/	EXFAITH-V$_{\text{NASAL}}$	V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$	*V$_{\text{NASAL}}$
a. [pãl]	*	*!	*
b. ☞ [pal]	*		

(iv) Input: /pãl/	EXFAITH-V$_{\text{NASAL}}$	V$_{\text{NASAL}=\alpha}$C$_{\text{NASAL}=\alpha}$	*V$_{\text{NASAL}}$
a. ☞ [pãl]		*	*
b. [pal]	*!		

2.2.4 Simplicity in the logical structure of constraints

Obviously the constraint system (2.22) just discussed was not entirely wrong. It described the same data as the original system, with the same number of constraints. Two of the constraints were plausibly grounded. So how can a single further constraint get the data right while being rather implausible? Are there any clues to be read off the formal structure of the constraint that might tell us that something is not quite right? Indeed there are: EXISTFAITHFUL-V$_{\text{NASAL}}$ is a combination of a faithfulness and a markedness constraint. The relevant effect is reached if we form a logical conjunction of the ID-IO(nasal) and the *V$_{\text{ORAL}}$N constraints:[11] (2.23).

[11] This way of conjoining two constraint specifications should not be confused with the OT concept of local conjunction (see e.g., Kager 1999, 392ff). The local conjunction of two constraints C^1 and C^2 relative to a domain δ is an additional, rankable constraint that is violated iff both C^1 and C^2 are violated within the same instance of δ. Logically, this corresponds to a *disjunction* of the individual constraint specifications (which is false iff the two disjuncts are false), rather than a conjunction.

(2.23) Combination of Ident-IO(nasal) and *V_{ORAL}N
The specification of the feature [nasal] of an input segment must be preserved in its output correspondent
and
before a tautosyllabic nasal, vowels must not be oral.

The combined constraint (2.23) is violated by all candidates violating either of the two constituent constraints. It is also violated just a single time if both are violated (for candidate b. in (ii)).

As the comparison in (2.24) shows, the combination behaves exactly like our hypothetical constraints ExistFaithful-V_{NASAL}, except for candidate b. in (iii). Looking back at (2.22) however, this difference does not have any effect, since in (iii) both candidates violate ExistFaithful-V_{NASAL}, and the remaining constraints make b. the winner under any ranking.

(2.24) Comparison of ExistFaithful-V_{NASAL} and the Combination of Ident-IO(nasal) and *V_{ORAL}N

(i) Input: /pan/	ExFaith-V_{NASAL}	Combination	Id-IO(nasal)	*V_{ORAL}N
a. [pãn]	*	*	*	
b. [pan]	*	*		*

(ii) Input: /pãn/	ExFaith-V_{NASAL}	Combination	Id-IO(nasal)	*V_{ORAL}N
a. [pãn]				
b. [pan]	*	*	*	*

(iii) Input: /pal/	ExFaith-V_{NASAL}	Combination	Id-IO(nasal)	*V_{ORAL}N
a. [pãl]	*	*	*	
b. [pal]	*			

(iv) Input: /pãl/	ExFaith-V_{NASAL}	Combination	Id-IO(nasal)	*V_{ORAL}N
a. [pãl]				
b. [pal]	*	*	*	

The lesson to be learned from this hypothetical example is that one should be skeptical about constraints that cannot be formulated in a straightforward and simple way (cf. also Grimshaw 1998, arguing for logically simple constraints). These are likely to be combinations of simpler constraints, so a constraint system based on the more primitive constraints should be considered.

On the other hand, a system with a small number of simple constraints that predicts the typological data correctly suggests that one is on the right track, even if one does not yet have a thorough independent motivation for every single constraint. The logical structure of constraints is discussed in more detail in sec. 4.4.

2.3 Summary

In this chapter, the components of a linguistic OT account were demonstrated with the example of Grimshaw's (1997) analysis of inversion. The paramount role of constraint interaction as an explanatory device – which will be at the centre of discussion throughout this dissertation – was pointed out, and the mechanics of cross-linguistic empirical predictions through factorial typology were demonstrated.

Factorial typology with its exactly specified relation between the assumptions made by a linguist (in the form of constraints) and their *cross-linguistic* empirical consequences is one of the major innovations of the OT framework, going along with the departure from classical grammar models based on the concept of formal grammars which define sets of strings. In the classical string-language-oriented view, the analyses assigned to strings are subordinate to the main goal of specifying the correct string language. In the OT view, the objects of the theory are crucially pairings of surface forms and underlying content representation, as the discussion of sec. 2.2 showed. With this move, the learning task for a grammar model receives an entirely new character: learning no longer means trying to get the string language correct by making decisions on a subset of the rule specifications in a formal grammar (*parameters*, which appear rather arbitrary from a formalist point of view). Now learning means checking whether the pairing of form and content observed is predicted as optimal by the learner's own system, and if necessary correcting the constraint ranking. (In sec. 3.3, I will address learning in some more detail.)

Chapter 3

Some observations about OT syntax

In this chapter, some important observations about the basic components of a *syntactic* OT system are made – postponing detailed formal considerations to chapter 4. Sec. 3.1 contrasts the options for motivating OT constraints in phonology with the options available for a syntactic account. Sec. 3.2 addresses faithfulness violations in OT syntax and consequences for candidate generation; sec. 3.3 introduces the OT learning theory and discusses implications for the character of the input.

3.1 On the motivation of syntactic OT constraints

The formal rigour of typological predictions illustrated in sec. 2.2 is clearly one of the strengths of the Optimality-theoretic approach. At the same time, the examples discussed in that section point to a potential methodological problem – in particular when we are moving from phonology to syntax: above, we were dealing with toy examples of three constraints which have a clearly observable effect. But what if there are more constraints and their effect on the observed data is more indirect? – both are the case with most syntactic constraint systems. More constraints give us a larger factorial typology to check, and what we have to check depends in part on theoretical assumptions. So it is not so easy to get an overview of the actual typological spectrum in the languages of the world. The question of whether or not a specific language type (like (2.8c) in sec. 2.2) exists may be hard to answer. Not finding any evidence for some language type in the typological literature does not imply that it is not a possible language type.

This does not mean that the typological criterion is less important for evaluating syntactic OT systems, but it suggests that occasionally one has to make do without rigorous evidence according to this criterion.

Unfortunately, the issue of independent, functional evidence for syntactic constraints is even more problematic. Syntactic constraints are based on abstract representations, which are only indirectly related to observable evidence. Thus, the form that the constraints take always depends in part on the kind of representations one assumes. This makes it hard to find theory-independent grounding for constraints as it can arguably be provided in the phonological domain (through phonetic grounding).

To a certain degree this reflects a problem that any theoretical account of syntax has – the value of the representations assumed can only be judged when looking at the interplay of all aspects of the theory. A special twist of the problem arises for OT syntax since the representations assumed are often inherited from another theoretical framework (GB, Minimalism, LFG). Obviously, part of what makes out this other framework is replaced by OT's mechanism of constraint interaction. This in turn may influence the "grounding" of the representations – or in other words, the same representation may be suitably motivated in the original framework, but may be foreign to the Optimality-theoretic variant of the framework.

There are a number of consequences one may draw from these circumstances. The ones picked up in this dissertation are the following:

- Syntactic OT systems should be formulated in a precise way; this should help one isolate the effect of particular constraints. In particular the principles governing candidate generation have often been left implicit so far.
- Ultimately, a computational simulation of a complex syntactic OT system should facilitate the checking of empirical, typological consequences of the assumed constraints etc.[1]
- Allowing only simple violable constraints (according to some precise measure of complexity) reduces the degrees of freedom of the system; working out the consequences of such a system should lead to insights about the character/usefulness of OT-style constraint interaction.
- For the formal and computational approach, it is important to know what types of cross-linguistic variation occur (word order variation, presence/absence of certain overt elements etc.); this allows for conclusions about the character of the candidate generation function *Gen* and the expressiveness of the violable constraints.

[1] While this dissertation does not provide a fully implemented system for general OT models, it discusses many of the relevant computational issues. For investigations that are compatible with certain restrictions discussed further down, a classical processing system like the LFG parser/generator XLE (Xerox Linguistic Environment) can be readily applied.

Generally, the focus in this dissertation is on formal and computational properties of syntactic OT systems and the role that these properties play in predicting certain empirical facts. Individual phenomena and particular sets of constraints for modelling them typologically are only used for occasional illustrations. (Quite obviously, the investigation of entire factorial typologies is impractical under this focus.)

3.2 Faithfulness violations in phonology and syntax

In this section, a central methodological principle of OT is identified (sec. 3.2.1). If this principle is taken seriously, the cross-linguistic observations discussed in sec. 3.2.2 for phonology and in sec. 3.2.3 for syntax enforce a particular liberty in the candidate generation *Gen* – impressionistically speaking, the deletion of material from the input and the addition of material to the output. In this section, the OT analyses are presented in a relatively informal way. In sec. 4.6, the issue will be reconsidered against the formalization of OT syntax in the LFG framework provided in chapter 4.

3.2.1 Constraint interaction as the main explanatory device

As has become clear from chapter 2, the key insight in the OT approach in phonology and syntax has been that variation between languages can be derived in a system assuming a universally invariant set of constraints on well-formed linguistic structures, where it is only the relative ranking of these constraints that differs cross-linguistically. Technically, an OT system is thus set up as the combination of

(i) a candidate generation component (*Gen*) that – given some underlying form (the *input*) – produces a set of competing structures which all satisfy some inviolable principles, and

(ii) an evaluation component (*Eval*) that checks the candidate structures for constraint violations and determines the optimal (most harmonic) candidates relative to the constraint ranking of the language in question.

(The customary tableau notation focuses on component (ii), assuming the candidate set as given and illustrating the constraint violations of the individual candidates and the harmony evaluation across the candidates.)

This general set-up leaves quite some space for variation as to the implementation of a particular OT system for use in a linguistic study or a computational system. One may choose to assume a relatively restrictive set of inviolable principles (as part of *Gen*), leaving a fairly small set of alternatives for the optimization step, or one may assume very weak inviolable principles and leave most of the work to the interaction of violable constraints.

Of course, keeping the candidate space small has the practical advantage of making the optimization task more perspicuous to the theorist, and indeed most OT studies in the literature focus on just some small set of candidates considered relevant for the studied phenomenon. However, this practical move does not justify the conclusion that the overall system that OT theorists see themselves as contributing to has a *Gen* component doing that much work. To the contrary, a widely assumed methodological principle is:

(3.1) *Methodological principle of OT*
Try to explain as much as possible as an effect of constraint interaction.

This implies an overall OT model with a very weak *Gen* component.

As an end in itself, principle (3.1) would not be of much scientific value. What is behind it is the observation discussed in sec. 2.2: For certain linguistic phenomena, OT constraint interaction with its inherent *factorial typology* has been shown to successfully predict the space of cross-linguistic variation, including the systematic exclusion of certain logically possible languages. So the reason for following (3.1) is to investigate to what extent OT constraint interaction may serve as the key explanatory device in modelling linguistic knowledge in general. Evaluation of success in this investigation should be based on criteria like the following: Is the empirically observable typological space predicted based on a set of well-motivated constraints? The strong hypothesis of the Optimality-theoretic approach is thus that all (and only) the observed cross-linguistic variation can be explained as an effect of constraint reranking. A closer investigation of the formal and computational implications of this strong OT hypothesis is one way of checking to which degree the hypothesis is tenable. The present dissertation can be seen as an attempt to follow this path, focusing on the division of labour between *Gen* and *Eval*. An important question will be under what circumstances the processing tasks (parsing/recognition and generation) based on an OT model are decidable (Johnson (1998) observes a decidability problem for the general, unrestricted OT model).

The critical constraints for the decidability issues are faithfulness constraints that lead to a significant discrepancy between the input and the output when violated. This way, they may lead to an infinite number of candidates. Do we need such constraints?

The reasoning on this issue in this dissertation is as follows: In sec. 3.2.3, it is observed – rather informally – that a certain type of variation across the languages of the world exists (whether (i) expletive elements are used and (ii) pronominals may be dropped). If we want to model this type of variation as an exclusive effect of constraint interaction (following principle (3.1)), *Gen* has to have a certain property (generating particular faithfulness violations). The formal character of this property is discussed again in chapter 4. In chapter 6 the consequences for processing are addressed.

3.2.2 Epenthesis and deletion in phonology

Before going into the syntactic data, here is some background on deletions and epentheses as they are known from the phonological theory of syllable structure (cf. e.g., Kager 1999, ch. 3). An important markedness constraint of syllabic well-formedness is ONSET:

(3.2) ONSET
*[$_{\sigma}$V – 'Syllables must have onsets.'

Thus, when possible the underlying phoneme sequence is grouped into syllables in such a way that consonants will act as the onset of a new syllable: In Axininca Campa (an Arawakan language spoken in Peru), the input /no-N-č^{h}ik-i/ is syllabified as [noɲ.č^{h}i.ki]. However, if two vowels are adjacent in the underlying form (as in /no-N-koma-i/),[2] this is not possible. Since (3.2) ONSET is high-ranking in Axininca Campa, the language makes use of an epenthetical consonant in such cases: (3.3a).

(3.3) Consonant epenthesis in Axininca Campa (Kager 1999, 93)

a.	/no-N-koma-i/	[noŋkoma**t**i]	'he will paddle'
b.	/no-N-č^{h}ik-i/	[noɲč^{h}iki] (*[noɲč^{h}ik**t**i])	'he will cut'

This shows that faithfulness to the underlying input segments has to be a violable constraint. According to the Correspondence Theory account of (McCarthy and Prince 1995), this is formulated as an instance of the DEPENDENCE constraint: input-output correspondence (3.4).[3]

[2] Note that the assumption of this underlying form for (3.3a) is based on the observation that both examples in (3.3) end in the same underlying suffix.

[3] Correspondence is a relation between elements in two strings s_1 and s_2, where DEPENDENCE demands that every element of s_2 has a correspondent in s_1. Its dual is MAXIMALITY demanding that every element of s_1 has a correspondent in s_2. (Cf. also Kager 1999, 205.)

(3.4) Dep-IO
Output segments must have input correspondents. – ‘No epenthesis’

The opposite option, dropping one of the two adjacent vowels, exists also. In languages like Modern Greek, the conflict between (3.2) Onset and faithfulness is resolved in this way: /kanona-es/ (‘rules’) is realized as [kanones].[4] Hence, we have another violable faithfulness constraint – an instance of Maximality:

(3.5) Max-IO
Input segments must have output correspondents. – ‘No deletion’

With all three relevant constraints in place, we can have a look at the tableau for (3.3) in Axininca Campa:

(3.6)

(i) Input: /no-N-koma-i/	Onset	Dep-IO	Max-IO
a. ☞ [noŋ.ko.ma.**t**i]			*
b. [noŋ.ko.ma]		*!	
c. [noŋ.ko.ma.i]	*!		

The factorial typology of the three constraints (3.2), (3.4) and (3.5) leaves open a third option:[5] ranking both faithfulness constraints above the markedness constraints. The result are onset-less (but faithful) output structures as they exist in many languages, including English.

This typology tells us a lot about the candidate generation function *Gen*. Since it is universal (by assumption), it must produce candidates with epentheses and deletions in all languages. In the outcome, the freedom of generating infinitely many candidates undergoes the filter of constraint interaction, which limits the number of grammatical sentences for a particular given language.

3.2.3 Syntactic variation across languages – the case of expletive and null elements

Expletive elements

Now turning to syntax, the types of cross-linguistic variation one can observe motivate the assumption of a similarly liberal *Gen* function on the level of words

[4] Thanks to Effi Georgala for help with the Greek data.

[5] There are six possible rankings of the three constraints, but the relative ranking of the two highest-ranking constraints never plays a crucial role.

as on the level of phonological segments. The cross-linguistic differences between the surface strings of winning candidates are very basic ones and were already discussed in the earliest work on OT syntax (cf. Grimshaw 1997): for syntactic reasons, some languages require the use of expletive elements where other languages do not (cf. the expletive *do* in English (3.7a), vs. the German example (3.7b)).

(3.7) *Expletive do in English*

a. Who did John see

b. Wen sah John
whom saw J.

According to the methodological principle of OT (3.1) discussed in sec. 3.2.1, this contrast should be explained as an effect of constraint interaction; i.e., the structures of both sentences have to be competitors in the same candidate set. The candidate winning in English is a case where the surface string contains some additional element not present in the underlying *input*. So, quite similarly as in OT phonolgy, faithfulness to the input has to be a violable constraint in OT syntax. In English, it is outranked by some structural markedness constraint, thus giving rise to an unfaithful winner. The faithfulness constraint at stake here is input-output dependence: Dep-IO – we can assume exactly the same constraint as in phonology (3.4), interpreting words as the relevant output segments for syntax and semantic predicates as their input correspondents.

Note that one might also try to argue for the expletive status of *did* based only on a single language like English: one could point out the difference between minimal pairs of inverted and non-inverted clausal structures (*John saw her* vs. *Who did John see*), which suggest that the latter case contains an instance of overt material not present in the underlying form. However, this evidence would not exclude the possibility that the underlying form of questions contains some additional element that is being rendered faithfully in the English question. And if all languages behaved like English, *Gen* should not generate any choice for the questions. However, if one finds a cross-linguistic difference (as in (3.7) above), one can be sure that according to the OT assumptions, *Gen* has to provide both options.

Strictly speaking, the hypothesis of an underlying question-marking element cannot be excluded when other languages like German are taken into account that do not display this element overtly, since these other languages could rely on deletion, violating Max-IO (3.5). The underlying form is not directly observable, but it rather models some semantic concept of content. However, for this concept of content we do not have any theory-independent intuition about what might count as a segment. So, in a sense it is an arbitrary decision whether English is unfaithful – violating Dep-IO – or German is unfaithful – violating Max-IO. (Recall that a similar choice was discussed for the “polarity” of the Ident-IO constraint in sec. 2.2.3.) The latter choice would however result in a rather unorthodox theory, so we can savely keep to the former option.

(3.8) is a tableau showing that (3.7a) does actually arise as the winner of optimization in English, according to the analysis of (Grimshaw 1997).[6]

(3.8) *Optimization with unfaithful winner*

Input: ⟨ read(x, y), $x =$ Mary, $y =$ what ⟩	Op-Spec	No-Lex-Mvt	Ob-Hd	Dep-IO (Full-Int)	Stay
a. [$_{\mathrm{VP}}$ Mary reads what]	*!				
b. [$_{\mathrm{CP}}$ what **e** [$_{\mathrm{VP}}$ Mary reads t]]			*!		*
c. [$_{\mathrm{CP}}$ what **reads**$_i$ [$_{\mathrm{VP}}$ Mary **e**$_i$ t]]		*!			**
d. ☞ [$_{\mathrm{CP}}$ what **does**$_i$ [$_{\mathrm{IP}}$ Mary **e**$_i$ [$_{\mathrm{VP}}$ read t]]]				*	**
e. [$_{\mathrm{CP}}$ what **e** [$_{\mathrm{IP}}$ Mary **does** [$_{\mathrm{VP}}$ read t]]]			*!	*	*

The constraints Op-Spec, Ob-Hd and Stay have already been introduced in sec. 2.1 above. No-Lex-Mvt (3.9) is an additional markedness constraint Grimshaw assumes:

(3.9) No Lexical Head Movement (No-Lex-Mvt)
A lexical head cannot move.

In Grimshaw’s terminology the Dep-IO faithfulness constraint is called Full Interpretation (Full-Int). As (3.8) shows, the fact that No-Lex-Mvt outranks Dep-IO causes candidate d. to win over c. Under a ranking in which both Ob-Hd and Dep-IO dominate No-Lex-Mvt, candidate c. would be the most harmonic, i.e., we would have a language with inversion of the main verb.

Another well-known example for an expletive element is the English *it* filling the structural subject position in (3.10a) (cf. Grimshaw and Samek-Lodovici 1998, sec. 4). Semantically, the verb *seem* takes just a proposition (realized as the *that*-clause) as an argument. Comparison with Italian (3.10b) shows that again, this type of expletive does not occur universally, so in English we have a Dep-IO violation.

[6] Grimshaw assumes that auxiliaries are always inserted in I^0, thus there is no candidate *what does Mary read* without an intermediate IP projection.

(3.10) *Expletive pronoun in English*

a. It seems that John has left

b. Sembra che Gianni è andato
seems that G. is gone

(3.12) and (3.13) show the tableaux deriving this effect in English and Italian, according to the analysis by Grimshaw and Samek-Lodovici (1998) and Samek-Lodovici (1996). Subject (3.11) is the relevant markedness constraint.[7]

(3.11) Subject
The highest A-specifier in an extended projection must be filled.

(3.12)

Input: ⟨ seem(x), $x =$ ⟨ leave(y), $y =$ John ⟩⟩	Subject	Dep-IO (Full-Int)
a. seems [that . . .]	*!	
b. ☞ it seems [that . . .]		*

(3.13)

Input: ⟨ sembra(x), $x =$ ⟨ andare(y), $y =$ Gianni ⟩⟩	Dep-IO (Full-Int)	Subject
a. ☞ sembra [che . . .]		*
b. *expl* sembra [che . . .]	*!	

Null elements

If we look at Italian examples with verbs that clearly take a semantic argument like *cantare* ‘sing’, we have an example of the opposite type of faithfulness violation, a Max-IO violation: In *Pro-drop* languages, there is no overt correspondent for the subject pronoun referring to a topical entity (cf. Grimshaw and Samek-Lodovici 1998, sec. 3). English (3.14a) contains an overt subject pronoun, Italian (3.14b) does not. This demonstrates that it is possible to leave some *input* material unrealized to satisfy some high-ranking Markedness constraint.

[7] The “highest A-specifier” refers to the specifier-to-IP position.

(3.14) *Dropped pronominal in Italian*

a. He has sung

b. _ ha cantato
has sung

Grimshaw and Samek-Lodovici's analysis deriving these results relies on the additional constraint (3.15) DropTopic, which favours the *pro-drop* option, provided the element in the previous coreferent with the dropped subject pronoun is already the topic.

(3.15) DropTopic (Grimshaw and Samek-Lodovici 1998, 194)
Leave arguments coreferent with the topic structurally unrealized. Failed by overt constituents which are coreferential with the topic.

English (3.16) and Italian (3.17) differ in the relative ranking of DropTopic and Max-IO (called Parse in Grimshaw and Samek-Lodovici's terminology). In sec. 5.3.2, I will come back to this analysis discussing the status of the DropTopic constraint.

(3.16)

Input: ⟨ sing(x), x = topic, x = he ⟩	Max-IO (Parse)	DropTopic	Subject	Dep-IO (Full-Int)
a. has sung	*!		*	
b. ☞ he has sung		*		

(3.17)

Input: ⟨ cantare(x), x = topic, x = lui ⟩	DropTopic	Max-IO (Parse)	Dep-IO (Full-Int)	Subject
a. ☞ ha cantato		*		*
b. lui ha cantato	*!			

3.2.4 Consequences for *Gen*

As already stated in sec. 3.2.1, identifying something as an effect of constraint interaction implies that the other component of an OT system, *Gen*, has to leave open all options for this effect. Assuming faithfulness as a violable constraint means that candidate generation has to be insensitive to the preservation of the *input* information in the surface string.

Assuming a predicate-argument structure with additional tense and aspect information as in (3.18) as *input* (cf. Grimshaw 1997, 375), we are thus faced with all items in (3.19) as possible candidates, most of them violating Dep-IO or Max-IO or both (violating Max-IO twice will for instance lead to a phonologically empty candidate: (3.19f)).

(3.18) Input: laugh(x), x = Ann, tense = past

(3.19) a. Ann laughed
b. Ann did laugh
c. it laughed Ann
d. laughed
e. Ann
f.
g. she laughed
h. she did
i. Ann yawned
j. John yawned
k. Ann saw him, etc.

With an appropriate number of Max-IO violations (precluding the underlying input form to appear overtly) and Dep-IO violations (introducing material that normally denotes something else) we can arrive at every conceivable word string, no matter what the input is. At first sight, such an OT system clearly seems computationally intractable due to an incontrollable candidate space. But as I argue in the following chapters, the LFG-based conception of OT syntax (chapter 4) provides a natural framework for modelling the intuitions about faithfulness violations addressed in this and the previous section in a way that allows one to structure the candidate space adequately for computational processing (chapter 6).

3.3 Learning and the character of the input

3.3.1 Learning in OT

As mentioned in the introduction chapter 1, it is one of the outstanding features of the Optimality-theoretic approach that it is intimately coupled with a formal theory of language learning. This means that not only can predictions for a single language be tested empirically – based on a formal specification of *Gen*, the constraints and the language-specific ranking. But moreover, the validity of a set of constraints can be determined empirically by using a learning algorithm on corpora of language data. For typologically different languages, the algorithm should arrive at different rankings over the constraint set provided as input.

Two approaches to the learning problem have to be mentioned: the original *Constraint demotion algorithm* of (Tesar 1995; Tesar and Smolensky 1998), and the *Gradual learning algorithm* of (Boersma 1998; Boersma and Hayes 2001).

Constraint demotion

The *Constraint demotion algorithm* (Tesar 1995; Tesar and Smolensky 1998)[8] should be seen as an idealized and abstract algorithm whose main purpose is to show that a formal OT system is indeed learnable. Besides the set of constraints and the *Gen* function, the algorithm requires language data which contain an explicit specification of the underlying (input) form.

Initially, all the constraints are assumed to be unranked with respect to each other. The algorithm proceeds by making the relative ranking of two or more constraints explicit on encountering evidence that is not consistent with the ranking built up so far, i.e., in case the current system makes an error. What is important to note is that only *positive* evidence is needed for getting the ranking correct. This is possible since it follows from the OT assumptions that knowing the winning candidate in a competition implies that all other possible realizations of the input are ungrammatical. So the ranking has to exclude all candidates but the winner. Since the constraints and *Gen* are known, the constraint marking (the number of stars in the tableau cells) of all candidates in a given competition are known. Now, the target ranking has to be such that for each losing candidate, the winner is more harmonic. So, we have to consider winner-loser pairs as in the schematic illustration in (3.20).

[8] See (Kager 1999, ch. 7) for a more thorough introduction.

(3.20) *Schematic illustration of winner-marks and loser-marks*

Candidates	Constraint marking
target winner	$*C^1$ $*C^2$ $*C^4$ $*C^5$
target loser	$*C^1$ $*C^3$ $*C^4$ $*C^5$ $*C^5$

constraints C^1, C^4: irrelevant (same number of violations)
constraint C^2: winner-mark
constraints C^3, C^5: loser-marks

The relevant constraints are those in which the winner and the loser differ: we can distinguish *winner-marks* (for constraints that the winner violates more often than the loser – C^2 in (3.20)) and *loser-marks* (vice versa – C^3 and C^5 in (3.20)). In the target ranking, at least one of the constraints with the loser-marks (e.g., C^3) has to be ranked above the highest constraint with a winner-mark (C^2 in the example). Else the winner would not be more harmonic than the loser.

At an early point in the process of building up the ranking for a given language, there may be many possibilities for getting some loser-mark constraint high enough in the ranking. However, some of these possibilities will lead to problems later on in learning. This would require a correction of decisions made earlier. The constraint demotion algorithm avoids the need for corrections by proceeding in a conservative way, at each step making the minimal commitment required for getting the current piece of data correct. This conservativity results if each of the winner-mark constraints is *demoted minimally*, i.e., just below the highest-ranking loser-mark constraint. (So, if the temporary ranking in the example was $C^2 \gg C^3 \gg C^5$, the constraint C^2 would be demoted between C^3 and C^5, to give us $C^3 \gg C^2 \gg C^5$.)

For a given candidate set, this *constraint demotion* step is performed repeatedly on all winner-loser pairs, until no further demotions occur. The algorithm converges in a stable ranking, independent of the order in which the winner-loser pairs are considered.

Gradual learning

One idealization of the constraint demotion algorithm that is clearly unrealistic for modelling the real learning task is the following: the algorithm is designed to work on a perfect sample of language data. A single piece of erroneous data (e.g., an utterance from a different language or a slip of the tongue) may cause a constraint demotion that is inadequate for the target ranking, but from which the learner may not recover (an infinite loop of demotions may follow).

This is the main motivation for Boersma's (1998) proposal of a gradual learning algorithm (see also Boersma and Hayes 2001), which is *robust* in the sense that a small amount of noise in the training data has no negative effect on the outcome of the learning process.[9] The key idea is that on encountering a piece of data that is incompatible with the current constraint ranking, no radical reranking is performed but just a gradual adjustment. The constraints are ranked on a continuous scale, and whenever a harmony evaluation is performed, a small amount of noise is added in determining the actual rank. On encountering a ranking error, the base value for all constraints with a deviating violation count on the winning candidate is adjusted by a small increment. If the observed ranking error originated from noise in the data, its effect is soon neutralized by other evidence. If on the other hand, the piece of data revealed a real problem in the ranking, additional evidence to the same effect re-enforces the tendency. This strategy ensures that only effects with a sufficiently high frequency in the training data do actually alter the constraint ranking effectively.

The gradual learning approach requires a revision in the conception of the constraint ranking and constraint evaluation: under the standard *discrete* ranking of constraints, a gradual adjustment of the relative ranking of constraints is not possible. Boersma assumes the constraints to be ranked on a *continuous* scale. Furthermore, constraint evaluation is stochastic, i.e., some limited random noise (with a normal distribution) is added when the effective ranking – the *disharmony* – of the constraints is determined. So, each evaluation is based on a slightly different effective constraint ranking. This ensures that the constraints maintain a safety margin in their ranking difference and the system can stabilize.

When an error arises in learning (i.e., a piece of data is not predicted to be the winner under the learner's current ranking), the constraint ranking is not altered according to the minimal demotion regime as discussed above, but rather according to a maximal promotion/demotion regime. This means that *all* winner-marks are demoted on the continuous scale by a small increment and *all* loser-marks are promoted slightly.

For all those relative constraint rankings that are reflected with a sufficient frequency in the data, the gradual learning algorithm will also separate the constraints on the scale sufficiently for the random noise to be ineffective. So, despite the stochastic architecture, a categorical behaviour arises for those constraints. However, for phenomena that show variation in the data, the constraints will stay within the span of the random noise. For those phenomena, the effect of the gradual learning is that the frequencies observed in the data are being remodelled in the constraint ranking. So the probability distribution of the data generated by the OT system reflects the probability distribution in the observed data. This makes the stochastic OT approach very attractive for modelling optionality[10] (Asudeh 1999) and frequency effects.

[9] For a critical assessment of the gradual learning algorithm, see (Keller and Asudeh 2001).

3.3.2 Criteria for learnability – implications for the input

Both learning algorithms sketched in the previous subsection are error-driven, i.e., it is crucial that the learner recognize the need for an adjustment in her constraint ranking. This need arises when for a given input, the winner predicted according to the learner's current constraint ranking differs from the actually observed winner. Almost trivially, this situation can only be recognized when the input for the observed winner is known.

In the idealization addressed above, one assumes that the input is given in the training data, along with the output form. However, realistically, the learner has to infer the underlying input form from the observed output and the general context of utterance.[11] If based only on the linguistic output form, this inference is non-trivial, since the input-output mapping may be highly ambiguous (most notably due to the possibility of faithfulness violations).[12] Still, human learners do not seem to have problems with this inference. Presumably this is due to the predominant role played by the general context of utterance. If this conjecture holds true, language learning is only possible once the general cognitive abilities put the child in a position to *understand* the content of the utterance from which it learns – or at least relevant aspects of the content.

Note that here, one has to distinguish the learning situation from normal language use. For normal language comprehension, of course no independent inference of the content of an utterance is needed (else verbal communication would be redundant). A hearer may have the linguistic utterance as the only information, so she has to rely on the predictions of the current state of her OT

[10] For discussion of optionality in standard OT, see (Müller 1999; Schmid 2001).

[11] Note that assuming the input to be explicitly represented in the candidate structures, even if deletions occurred (as ensured by the original *containment* condition of Prince and Smolensky 1993), does not change the situation, since the learner will only have access to the surface form of the candidate representations.

[12] A deep investigation of the task would have to take the bidirectional optimization architecture to be discussed in sec. 5.3 into account. This would make it even clearer that error-driven learning can work only if there is an independent way of judging whether the underlying interpretation predicted by the current OT system is correct (i.e., it corresponds to the message that the speaker intended to convey). Tesar and Smolensky (1998) assume the device of *robust interpretive parsing* to determine the underlying form (which we might view as a comprehension-based – or interpretive – optimization based on the strong bidirectionality account to be discussed in sec. 5.3). However, the assumption of such a device does not make the need for restriction (3.21) below redundant. It only provides a characterization of the inference process.

system. However, in this mode an error cannot be detected, so learning steps are impossible.

As these considerations about the prerequisites for learning suggest, the idealization of providing both input and output in the training data is not so far off.[13] The child's understanding of the learning situation provides enough independent information to make the task of input reconstruction from the output feasible. However, if this reasoning is right, certain restrictions follow for the character of the input we may assume for an OT system.[14]

(3.21) *Restriction on the character of the input*
All aspects of the OT input must be such that they can be in principle inferred from the general context of utterance.

A simple way of satisfying this restriction for OT syntax is to follow standard assumptions and work with an input that consists of the truth-conditional semantics of the utterance. But (3.21) is also compatible with a more finely structured input including further "pragmatic" clues, such as information structural status etc.

Note that it is not stated that for an arbitrary utterance, it must be possible to effectively infer all aspects of the input. The restriction is much weaker, demanding that the input information has to be of a character that can at least be inferred from the context under favourable circumstances. For instance, it sanctions the inclusion of speakers' intentions in the input, which are not normally clear in a conversation, but which may be deducible in a particular situation. A constraint relying on such input information may be difficult to learn, but it is nevertheless possible if a sufficient amount of "training material" – utterances in certain conversational contexts – are available. (And if we think of irony or sarcasm, which one might want to treat as very intricate forms of faithfulness violations, it is hard to imagine how one can learn to assess them without ever having seen a rather obvious case of them.)

Since the restriction (3.21) is formulated so weak, it may appear almost ineffective; however it *does* exclude the assumption of a highly abstract concept of input with no connection to the utterance situation at all. Such a concept of input has been proposed to deal with the phenomenon of language-particular ineffability (Legendre, Smolensky, and Wilson 1998), discussed briefly in the following section.

[13] See also (Kager 1999, sec. 7.5.3) for a discussion of learning without given inputs.

[14] I would postulate this restriction not only for OT syntax, but also for the inputs in OT phonology. The assumption of input-level distinctions that get neutralized in the output is only justified when the learner can exploit independent evidence for this – for instance from a morphologically related form not displaying the neutralization effect. (For example, the [t] in the Axininca Campa example (3.3) [noŋ.ko.ma.**t**i] can only be identified as epenthetical if the learner realizes that (i) [noŋ.ko.ma.**t**i] is future tense, (ii) in the general case the future morpheme /-i/ appears without the t, and (iii) the t is not part of the verb stem.)

3.3.3 Language-Particular Ineffability

One of the puzzles for the Optimality-theoretic approach is how to account for facts where in a particular language, there is no grammatical way of stating a certain state of affairs, while this is perfectly possible in another language. This phenomenon is called language-particular ineffability. The standard example are multiple *wh*-questions in Italian (although they are often just discussed in the abstract). The English question (3.22), transferred literally into Italian yields an ungrammatical sentence: (3.23); and there is no other grammatical way of expressing this thought.[15]

(3.22) Who ate what?

(3.23) (Zeevat 2000, (2))

*Chi ha mangiato che cosa?
who has eaten what

The phenomenon constitutes a well-known problem for the Optimality-theoretic approach: optimization is defined in such a way that there is at least one winning candidate for every competition. Assuming furthermore that all competitions are universal (apart from the aspect which candidate wins), the grammaticality difference between English and Italian is unexpected. For the competition that (3.22) is the winner of in English (with the input in (3.24)), there should be some winner for Italian too.

(3.24) $\langle\ \text{eat}(x,y),\ x = \text{who},\ y = \text{what}\ \rangle$

Legendre, Smolensky, and Wilson (1998) propose a solution to this puzzle: they assume a highly abstract input, which they call *Index* in order to circumvent potential derivational connotations. The only purpose of this Index is to define candidate sets for optimization; it is unrelated to anything playing a role in a particular application of the grammar in language production. To make this clear Legendre et al. (1998) argue for an *inventory view* of the OT grammar. The most important consequence of this abstract view of the input/Index is that the part of the candidate structures that fixes their interpretation (the

[15] At least in a single clause.

logical form/LF) can be affected by faithfulness violations. So the candidates in a competition need no longer have the same interpretation.

This set-up opens up the possibility of a neutralization account for the ineffability data: both in Italian and in English, we have two competitions with the following two inputs/Indices:

(3.25) a. $\langle$ Q$_i$ Q$_j$ eat(x_i, y_j) $\rangle$
b. $\langle$ Q$_i$ eat(x_i, y), $y =$ something (indefinite) $\rangle$

(3.25a) is the interpretation for the multiple *wh*-question as in (3.24) (with explicitly marked scope, using Q-operators which bind variables in the argument positions). (3.25b) is the interpretation of a different question, with just a single *wh*-operator asking for the subject, while the object is indefinite.

In English, the two competitions have different winners: (3.22) for (3.25a) and (3.26) for (3.25b).

(3.22) Who ate what?

(3.26) Who ate anything?

In Italian, neutralization occurs, and we get the same candidate – presumably something like (3.27) – as the winner in both competitions.[16]

(3.27)	Chi	ha	mangiato	qualche cosa?
	who	*has*	*eaten*	*anything*

This is because in Italian, a markedness constraint that is violated by multiple *wh*-questions (*Absorb, according to Legendre et al. 1998) is ranked higher than faithfulness to the input/Index LF. As the relevant faithfulness constraint Legendre et al. (1998) assume a constraint Parse(wh), which would be Ident-IO(wh) in the terminology adopted in the dissertation. So the conflict that English resolves at the cost of violating *Absorb is resolved in Italian at the cost of a winner whose LF is unfaithful to the input/Index LF.[17] Note that the conflict does not arise for the simple *wh*-question input (3.25b), since having a single question operator does not violate any relevant markedness constraints.

The competition for (3.25a) is sketched in tableau (3.28). Candidate a. uses absorption to make sure that the two question operators are interpreted correctly; candidate b. uses adjunction for the same purpose; candidate c. unfaithfully drops the *wh*-character of the object argument to avoid the problem. In English, candidate a. wins. With Ident-IO(wh) ranked lowest, candidate c., which has a meaning that is different from the input, becomes the winner (as in Italian). Note that c. has a different meaning than the input.

(3.28)

Input: $\langle$ Q$_i$ Q$_j$ eat(x_i, y_j) $\rangle$		*Adjoin	Ident-IO(wh)	*Absorb
a. ☞	who$_{i[j]}$ t$_i$ ate what$_{[j]}$			*
b.	who$_i$ what$_j$ t$_i$ ate t$_j$	*!		
c.	who$_i$ t$_i$ ate anything		*!	

For comparison, here is the corresponding part of a tableau for the alternative input (3.25b), in which the constraints focused on here take no effect:

(3.29)

Input: $\langle$ Q$_i$ eat(x_i, y), $y =$ something (indefinite) $\rangle$		*Adjoin	Ident-IO(wh)	*Absorb
a. ☞	who$_i$ t$_i$ ate anything			

One should bear in mind that these results have to be regarded under the inventory view of optimization. This means it is inappropriate to think of ineffability in the following naive way: when Italian speakers have in mind a message like (3.25a), they will try to produce an utterance; but due to the way the constraints are ranked Italian speakers are bound to fail conveying the message, so they will say something else instead. The input/Index has no status

[16] For the detailed discussion of their approach Legendre et al. (1998) use Chinese examples – I am simplifying their discussion here, filling in examples for the discussion of Italian. Roberta d'Alessandro (p.c.) points out that a more natural way of expressing the existentially quantified object with *eat* in Italian would exploy an understood object:

(i) Chi ha mangiato?

The argumentation would go through with this form as the neutralization target too, but I wanted to avoid adding Max-IO violations as additional faithfulness effects to the present discussion.

[17] Another option of resolving the conflict is by fronting both *wh*-words, as Bulgarian does, but this violates another markedness constraint *Adjoin, which also dominates the faithfulness constraint in Italian.

in actual language use, it merely defines the inventory of linguistic structures available in a language. Multiple *wh*-questions are not available in Italian, so speakers will not try to use them.

3.3.4 The problem for learnability

The abstract view of the input/Index assumed by Legendre et al. (1998) works fine for an adult OT system with the constraint ranking fixed – and it works also for the idealized learning task, in which the training data include an explicit indication of the input/Index. As discussed in sec. 3.3.2, this idealization is arguably even justified as a model for real language learning as long as the input keeps the semantic content fixed across all candidates. Assuming the semantic input representation to be known in learning allows one to factorize out all kinds of general cognitive abilities involved in language learning, without making any unjustified idealizations: at least in favourable contexts the semantic input will be effectively deducible, which suffices to guarantee learnability over time.

However, for the abstract input/Index approach, it is a totally unnatural assumption that information about the input/Index is context-deducible for the learner: By assumption there is no connection between the utterance situation and the input/Index LF (as opposed to the candidate's LF, which is potentially unfaithful to the input/Index LF). In other words, when the neutralized Italian *who ate anything* (3.27) is uttered by an adult, the learner cannot tell whether it is the winner of a competition (3.28) or (3.29) – competitions are abstract and determine only the inventory.

But then there is no way of learning a language with a low-ranking LF-sensitive faithfulness constraint.[18] At the beginning, IDENT-IO(wh) has the same ranking level as the markedness constraints *ADJOIN and *ABSORB (they are all in the same constraint *stratum*). Then the learner will always hear neutralized data (since no others are in the adults' inventory). What should cause the learner to assume the more complicated competition (3.28) rather than (3.29)? Note that only the former would trigger the demotion of IDENT-IO(wh) required for adult Italian.

Even if there were some way of enforcing this move, it is not clear whether the option of assuming low-ranking LF-faithfulness is sufficiently constrained. Is there anything that would keep learners from re-interpreting a piece of evidence for which their current ranking predicts wrong results under the assumption of an LF-faithful winner? At least, the complexity added by the possibility of assuming an LF-unfaithful winner is enormous. Essentially, any semantically relevant feature of the training data evidence can be reconstructed as rendered unfaithfully, leading to a great numbers of possible abstract competitions. So it is highly likely that some of the learner's errors that should trigger learning steps involving markedness constraints (according to the error-driven scheme), will be incorrectly attributed to LF-unfaithfulness.

[18] If one could assume explicit negative evidence in learning, the situation would be different of course. But it is one of the basic tenets of the OT learning theory to assume only positive evidence.

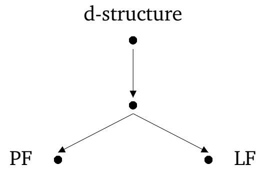
Learning is only a side issue in this dissertation, but I take the concerns discussed here as a further basis for enforcing the restriction on the character of the input (3.21) introduced in sec. 3.3.2. The interpretation of the candidates has to be fixed by the input/Index. This excludes the derivation of language-particular ineffability proposed by Legendre et al. (1998), but as will be discussed in sec. 5.3.1 and sec. 5.3.4, the assumption of bidirectional optimization provides the basis for a different explanation that avoids the learnability problems discussed here.[19]

3.3.5 The non-derivational view of the input-output connection

At this point, I should note that while for learnability reasons I do not follow Legendre et al. (1998) in the assumption of LF-unfaithful candidates, the insistence on an inventory view of optimization is very helpful – especially for derivational syntactic theories embedded in OT. (For inherently non-derivational approaches like Optimality-theoretic Lexical-Functional Grammar, OT-LFG, the danger of getting caught in a misleading thinking is much smaller for this matter.)

In a (Chomskyan) derivational account of syntax, each candidate analysis is a derivation, starting out from a d-structure representation and resulting in a phonetic form (PF) and a logical form (LF) – known as the Y-model (3.30).[20]

(3.30) *The Chomskyan Y-model for syntax*

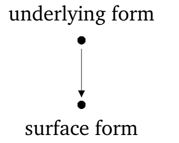


[19] Compare also (Smolensky 1998; Lee 2001; Morimoto 2000).

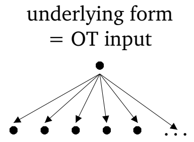
[20] See for instance (Chomsky 1995, ch. 1; Haegeman 1994).

On a technical level, this seems to suggest a suitable parallel with OT phonology: generative phonology is also based on a derivational process from an underlying, “deep” structure to a surface form that is realized phonetically (3.31). This permits a straightforward visualization of candidate generation in OT as a parallel derivation following all possible paths simultaneously (3.32), and then picking the most harmonic candidate as the actual output. (The derivation of *all* candidates can of course only be meant metaphorically, since there may be infinitely many of them. Hence, even here an inventory perspective is more realistic.)

(3.31) *The generative model of phonology*

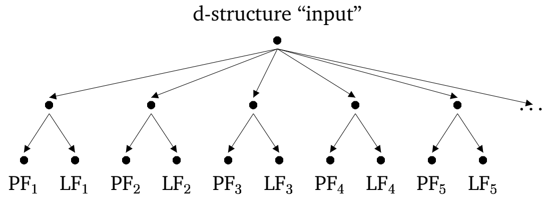


(3.32) *Candidate generation in OT phonology*



Treating the syntactic Y-model in parallel with the phonological model, gives us the following conception of syntactic OT:

(3.33) *Simple model of candidate generation with the syntactic Y-model*



However, this parallel misses an important conceptual difference: in phonology, the underlying form is indeed the interface to the conceptual level – by assumption, the underlying forms are what is stored in the mental lexicon along with the semantic and morphosyntactic information for the entry. Thus, we can envisage language production as a process involving the selection of some lexicon entry for which the stored phoneme string is retrieved and a phonological optimization is performed. Whether or not one adopts an inventory view or a particular input view does not have any important implications for the candidate set and for the learning situation. The learner will detect errors based on independently inferred underlying forms (e.g., assuming uniformity of stem forms across a morphological paradigm[21]).

The status of d-structure is *technically* closely related – it is the only “input” to the derivational process of syntax. However, contrary to what holds in the generative process of phonology, d-structure is not the sole interface to the conceptual parts of the cognitive system. The logical form/LF plays as important a role, fixing the scope of quantifiers etc. So modelling the OT input (the Index defining candidate sets) as only comprising the “input” of syntactic derivations (i.e. d-structure, or a numeration, that is an unstructured bag of lexical items) leads to unnatural results – at least when OT is viewed as more than just a technical device without any intuitive connection to the learning problem. For instance, LF_1 in (3.33) may have an interpretation different from LF_2 (see e.g., Sternefeld 1997).

The obvious solution is to extend the OT input to also comprise the LF information. For technical reasons, this is not compatible with a literally derivational OT model: the LF information for a candidate is not available until its derivation is finished.[22] Thus, it is impossible to keep up the derivational character of *both* the OT competition with its candidate-set-defining input *and* the individ-

[21] Compare footnote 2 on page 31 and footnote 14 on page 42.

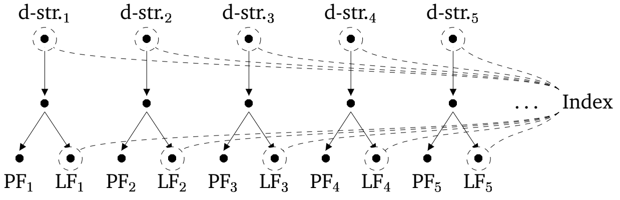
[22] This fact leads to a terminological conflict, which other researchers resolve in a different way. Heck et al. (2000) make a similar observation as the one just reported and come to the following conclusion: candidate set specification in syntax cannot be performed by the input (in the sense of *starting point of derivational syntactic analyses*) exclusively – some independent criterion is needed. This independent criterion (which they do not investigate any further) is what I continue to call input/Index in this dissertation (with the sole function of specifying the candidate set).

An independent issue discussed in (Heck et al. 2000) is the question to what extent the input has to be referred to when checking faithfulness constraints. With the rich representations assumed for syntactic candidates, they conclude that separate bookkeeping of the input is redundant in syntax. (This fact follows quite naturally if candidates are made precise in a formal framework, like in the OT-LFG account of (Bresnan 1996; Bresnan 2000; Kuhn 2001a), which I will introduce in chapter 4; the redundance of separate input-bookkeeping is addressed specifically in sec. 4.6.2, on page 114.)

The general conclusion drawn by Heck et al. (2000) – that in OT syntax, no input is required at all – should be seen against their specific terminological background. Certainly, candidate set specification on the basis of some partial linguistic information is needed throughout all OT approaches in phonology or syntax. However, the straightforward derivational view of candidate set specification is unproblematic for phonology, but incompatible with syntactic candidate analyses based on a standard derivational approach.

ual candidate analyses with the input d-structure. Legendre et al. (1998) give up the derivational view of OT candidate set generation from an input. Their abstract Index with its inventory-defining character applies at two points during the candidate derivation, as suggested by the sketch in (3.34): The specification of the Index consists of a d-structure with target positions for the operators (cf. (3.25) above), thus both the candidates' d-structure and their LF are fixed (subject to faithfulness violations). For the individual candidate analyses, Legendre et al. (1998) *do* still assume a derivational character; one may think of the Index as a filter on candidate derivations.

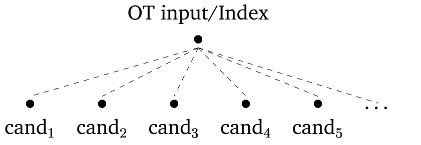
(3.34) *Candidates in OT syntax according to the inventory view of Legendre et al. (1998)*



An alternative solution to the problem is to assume static, non-derivational candidate representations. In principle, this could be realized by a redefinition of the Chomskyan framework: the chain representations standardly assumed for movements just have to be governed by strictly declarative principles. Then all structural levels will come into existence simultaneously, satisfying the well-formedness principles. This intuition seems to be underlying in much OT syntax work, although the derivational metaphor of movement tends to thwart intuitions occasionally. This is one of the motivations for assuming a strictly non-derivational basis for OT syntax as first proposed by Bresnan (1996, 2000) for the formalism of Lexical-Functional Grammar. This framework is also adopted in this dissertation (cf. the formalization in chapter 4).

The advantage of assuming non-derivational candidate representations is that the relation between the candidate-set-defining Index (or OT input) and the individual candidate analyses is conceptually simpler than in the model sketched in (3.34). The input/Index can be viewed as a formal object of the same type as the analyses (with the possibility that the input/Index is specified only partially). Faithfulness constraints and potential restrictions on the candidate generation function *Gen* can then be defined as an abstract relation between two formal objects of this type: what arises can be sketched as in (3.35), assuming that the dots represent formal objects comprising all structural levels relevant for a particular range of phenomena.

(3.35) *Strictly non-derivational view of candidate generation (for OT phonology or syntax)*



Although this conception is radically different from a simple derivational OT model (as sketched for phonology in (3.32)), it is isomorphic in its general structure. So the inventory view of OT competition, based on non-derivational candidate analyses emerges as a simple, but general framework adequate for all application areas of OT.

For this architecture, the term "input" might still be misleading if understood literally. However, firstly the terminological conflict with the candidate-level derivations of (3.34), which have their own inputs, has been eliminated; secondly, a metaphorical terminology suggesting abstract processes is rather customary for formal systems with a strictly declarative formulation (compare for instance automata theory). Therefore, I will continue to use the term *input*, even though the view of OT competition I adopt comes closer to the inventory view that Legendre et al. (1998) describe.

3.4 Summary

In this chapter, I identified some of the empirically relevant aspects of the OT system that a formalization must pinpoint and which furthermore have to be addressed in a computational implementation of an OT system. Sec. 3.1 provided a brief discussion of the problems of finding independent motivation for syntactic OT constraints – a circumstance, which can be viewed as motivation for doing foundational work on the formal and computational properties of syntactic OT systems. In sec. 3.2, differences across the languages of the world were investigated under one particular aspect: is there a difference in the practice of inserting semantically empty, i.e. epenthetical, material on the one hand, and in the overt realization of underlying material? As is well-known the answer is positive. This has consequences for the formal setup of OT syntax, in particular for the candidate space to be generated by the function *Gen* – assuming on takes the methodological principle seriously that one should try to explain all cross-linguistic differences through constraint interaction. In sec. 3.3, the basic assumptions of the OT learning theory were introduced, motivating a restriction on the character of the input. To ensure learnability it must be possible in principle to infer all aspects of the input from the utterance context. This excludes the assumption of LF-unfaithful candidates based on an abstract input. Furthermore, it was observed that a non-derivational formalization of an OT system has conceptual advantages and will therefore adopted in the remainder of this dissertation.

Chapter 4

The formalization of OT syntax in the LFG framework

In sec. 3.3.5, the conceptual advantages of a non-derivational framework for OT syntax (and OT systems in general) were discussed. A strictly non-derivational framework for OT syntax on a formally rigid basis was first proposed by Bresnan (1996, 1999, 2000). In her (Bresnan 2000, sec. 2), she presents a relatively close reconstruction of Grimshaw's (1997) OT system with the formal means of LFG, providing further arguments for the non-derivational approach.

In this chapter, I introduce an LFG-based formalization along Bresnan's lines, discussing choices in the exact specification against the background of the general empirical and learning issues of chapter 3.

There may be various reasons for adopting the LFG formalism as the basis for an OT account of syntax, including for instance the fact that a lot of typological research has been conducted in the LFG framework. For the present purposes, the main advantage of picking LFG as the base formalism is however that its formal and computational properties have undergone thorough research and that there are highly developed systems for processing the formalism. In fact, one might say that one goal in developing the OT-LFG model is to arrive at a sufficiently restricted formalism for OT syntax in general to allow computational processing – in much the same way as the design of the LFG formalism was guided by the objective of creating a framework that is expressive enough for an explanatory linguistic theory, while at the same time the processing tasks for grammars in that formalism are computationally tractable.

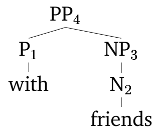
It should be noted that there is a fairly rich literature on the formalization and computational properties of OT phonology: Ellison 1994; Frank and Satta 1998; Karttunen 1998; Hammond 1997; Eisner 1997, and others. However, the approach adopted by these researchers is based on regular languages and regular relations, which are not expressive enough for modelling the syntactic domain.[1]

4.1 Background on the LFG formalism

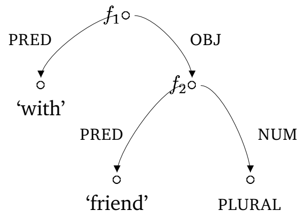
In this section, I present a brief review of the most important formal concepts of Lexical-Functional Grammar. For more details the reader is referred to the papers in (Dalrymple, Kaplan, Maxwell, and Zaenen 1995) (for aspects of the formalism) and to (Bresnan 2001) (for a current theory of syntax in the LFG framework).

LFG is a non-derivational, monostratal paradigm for the representation of grammatical knowledge, first defined in (Kaplan and Bresnan 1982). The key idea is to assume a number of different mathematical objects for the formal representation of different dimensions of linguistic utterances – most centrally the categorial dimension, represented through the tree-shaped c-structure, and the functional dimension, represented through the directed graphs of f-structure. As a simple example, the c-structure and f-structure for the prepositional phrase *with friends* is given in (4.1)[2] and (4.2).

(4.1) *C-structure*



(4.2) *F-structure*



[1] An interesting way of generalizing the results from formal/computational OT phonology to syntax is the generalization from regular languages to regular tree languages, as in (Wartena 2000). However, following the thread of computational-linguistic work on LFG and related formalism (as I do in this dissertation) has the advantage that much theoretical and implementational work is already in place and can be applied with little need for adjustments.

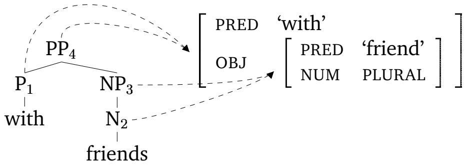
[2] The categories are indexed in this example to suggest that we are dealing with particular instances of the category types PP, P, NP, and N.

The arcs in the f-structure graph are labelled with features (PRED, OBJ and NUM); the atomic (i.e., leaf) f-structures are constants ('with', 'friend' and PLURAL). The common notation for f-structure graphs is as an attribute value matrix, like in (4.3).

(4.3)
$$\begin{bmatrix} \text{PRED} & \text{`with'} \\ \text{OBJ} & \begin{bmatrix} \text{PRED} & \text{`friend'} \\ \text{NUM} & \text{PLURAL} \end{bmatrix} \end{bmatrix}$$

The elements of the different structures stand in a correspondence relation, in the case of c- and f-structure a function ϕ mapping c-structure category nodes to f-structures. This function is often called a *projection*. In the example, ϕ maps both P_1 and PP_4 to f_1; f_2 is the ϕ image for both N_2 and NP_3. Note that the function ϕ need not be one-to-one, nor onto.[3] Sometimes, the function ϕ is shown explicitly in the representations, using arrows:

(4.4)



As the system is non-derivational it is important to note that one should think of all structures as coming to existence simultaneously. Projection from c-structure to f-structure should not be seen as a process; neither c-structure nor f-structure is prior to the other.

Knowledge about legal linguistic representations is formulated through propositions in a description language. For the different formal objects (trees and directed graphs), different description languages exist: the trees of c-structure are described by a context-free grammar,[4] the f-structure graphs by formulae of a feature logic – by so-called *f-descriptions*. A valid f-structure is

[3] Examples for f-structures that are not the image of any c-structure node are those representing arbitrary subjects like the subject of 'read' in the LFG analysis of sentences like *reading her book is fun*. In LFG, one does not assume a phonologically empty c-structure node for such a sentence.

[4] To be precise, a generalization over context-free grammars is used: the right-hand side of the production rules is not defined as a string of non-terminals/terminals, but as a regular expression over non-terminals/terminals. For each language generated there exists a weakly equivalent context-free language. The advantage of allowing regular expressions in the productions is that optionality etc. can be expressed without loss of generalization, as the following rule illustrates: VP → V (NP) PP*

defined as the minimal model satisfying all f-descriptions (plus the additional well-formedness conditions of Completeness and Coherence, which I will discuss briefly below).

(4.5) *Context-free grammar as a description of c-structure*

PP	→	P	NP
NP	→	N	
Lexicon entries:			
with	P		
friends	N		

(4.6) *Feature logic formulae as a description of f-structure*

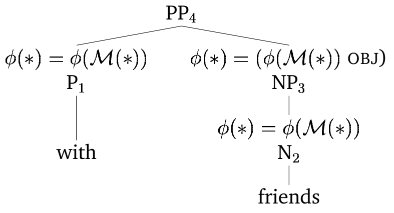
$(f_1\ \text{PRED}) = \text{`with'}$
$(f_1\ \text{OBJ}) = f_2$
$(f_2\ \text{PRED}) = \text{`friend'}$
$(f_2\ \text{NUM}) = \text{PLURAL}$

Obviously, a list of equations is interpreted conjunctively. But the feature description language contains also other Boolean connectives, so a formula can be negated, two formulae can be connected disjunctively etc.[5]

The correspondence relation between the structural dimensions is also expressed in the description language. Since the relation between c- and f-structure is a function, functional terms can be used to denote the f-structure corresponding to a given c-structure node. Thus, $\phi(\text{PP}_4)$ refers to the f-structure projected from PP_4, i.e., f_1; $\phi(\text{NP}_3)$ refers to f_2, etc. To allow for generalized statements about the c-/f-structure correspondence we want to be able to formulate *schemata* for f-descriptions, relative to a particular c-structure node. Such schemata can be attached to their category nodes (this is sometimes shown by writing the descriptions above the node in the tree representation). In the schemata, a metavariable $*$ can be used, which is instantiated to the particular c-structure node that the description is attached to.

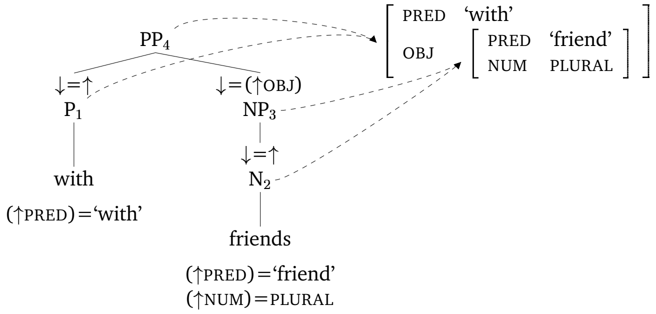
$\phi(*)$ denotes the f-structure projected from the node that the f-description is attached to. For expressing the relation between the f-structures projected from different nodes, we also need to be able to refer to the mother of the current node; this is done by $\mathcal{M}(*)$. Again, $\phi(\mathcal{M}(*))$ denotes the f-structures projected from the mother node. So we can stipulate that the f-structures projected from the current node and its mother node are identical by stating $\phi(*) = \phi(\mathcal{M}(*))$ (used for both P_1 and for N_2). The f-description attached to NP_3 stipulates that the f-structure projected from this NP is the value of the feature OBJ in the mother node's f-structure.

(4.7)


PP_4
$\phi(*) = \phi(\mathcal{M}(*))$
P_1
with
$\phi(*) = (\phi(\mathcal{M}(*))\ \text{OBJ})$
NP_3
$\phi(*) = \phi(\mathcal{M}(*))$
N_2
friends

Since $\phi(*)$ and $\phi(\mathcal{M}(*))$ are used extensively, there are abbreviations for these expressions, which are also called metavariables (for f-structures): ↓ and ↑. As becomes clear when the f-descriptions are written above the nodes, the ↓ symbol is mnemonic for the (f-structure projected from the) current node – the arrow points to it. Likewise ↑ is mnemonic for the (f-structure projected from the) mother node:

(4.8)


PP_4
$\downarrow = \uparrow$
P_1
with
$(\uparrow\text{PRED}) = \text{`with'}$
$\downarrow = (\uparrow\text{OBJ})$
NP_3
$\downarrow = \uparrow$
N_2
friends
$(\uparrow\text{PRED}) = \text{`friend'}$
$(\uparrow\text{NUM}) = \text{PLURAL}$
PRED 'with'
OBJ
PRED 'friend'
NUM PLURAL

The f-descriptions originating from the lexicon (or more generally, representing morpholexical information) are typically written below the phonological/orthographic form shown as the leafs of the c-structure tree. Nevertheless, ↑ is used to denote the preterminal nodes in the tree representation (P_1 and N_2 in the example). The phonological/orthographic forms – “with”, “friends” – should not be seen as full syntactic objects, but rather as indications of the phonological properties of the syntactic words, represented as P_1 and N_2.

[5] Apart from (defining) equations, there exist other primitive types of formulae: existential constraints about feature paths, which are true when the path exists (through some other defining equation); constraining equations, which are true when a feature bears a particular value (again, defined elsewhere); and set membership constraints.

With these means of expression, all grammatical knowledge can be encoded in a context-free grammar with feature annotations (or short: f-annotations). The annotations are schemata for f-descriptions to be attached to the category nodes in the c-structure tree. In the rule specification, f-annotations are typically written below the category that they are attached to.

(4.9) *LFG grammar: Context-free grammar with f-annotations*

$$\begin{array}{lcll}
\text{PP} & \rightarrow & \text{P} & \text{NP} \\
 & & \uparrow=\downarrow & (\uparrow\text{OBJ})=\downarrow \\
\text{NP} & \rightarrow & \text{N} & \\
 & & \uparrow=\downarrow &
\end{array}$$

Lexicon entries:

$$\begin{array}{lll}
\text{with} & \text{P} * & (\uparrow\text{PRED})=\text{‘with’} \\
\text{friends} & \text{N} * & (\uparrow\text{PRED})=\text{‘friend’} \\
 & & (\uparrow\text{NUM})=\text{PLURAL}
\end{array}$$

As mentioned briefly above, there are two additional conditions on the well-formedness of f-structures: Completeness and Coherence. These ensure that the subcategorization frame introduced by verbs, prepositions and other lexical categories is actually filled in syntactically. For example *John devoured* fails to satisfy Completeness, while *John yawned a car* is ruled out by Coherence. Technically this is achieved by specifying the selected governable grammatical functions (SUBJ, OBJ etc.) in the PRED value of verbs, prepositions etc., so we would have (↑PRED)=‘with⟨(↑OBJ)⟩’ and (↑PRED)=‘devour⟨(↑SUBJ) (↑OBJ)⟩’.[6] The composite PRED values may be seen as abbreviatory for feature structures as in (4.10).

[6] Under a more generalized account, only the semantic arguments are specified and the choice of particular grammatical functions is derived through mapping principles (Bresnan 2001, ch. 14).

(4.10) *Composite* PRED *values*

$$\left[\begin{array}{ll}
\text{PRED} & \text{‘with}\langle(\uparrow\text{OBJ})\rangle\text{’} \\
\text{OBJ} & \left[\begin{array}{ll}\text{PRED} & \text{‘friend’} \\ \text{NUM} & \text{PLURAL}\end{array}\right]
\end{array}\right]$$

expands to

$$\left[\begin{array}{ll}
\text{PRED} & \left[\begin{array}{ll}\text{FUNCTOR} & \text{with} \\ \text{ARGUMENT1} & \end{array}\right] \\
\text{OBJ} & \left[\begin{array}{ll}\text{PRED} & \left[\begin{array}{ll}\text{FUNCTOR} & \text{friend}\end{array}\right] \\ \text{NUM} & \text{PLURAL}\end{array}\right]
\end{array}\right]$$

The expanded feature structure encodes the functor/argument structure of the predicate[7] and forms the interface to a conceptual representation. The arc indicates that the value of the feature path PRED ARGUMENT1 and OBJ are the same f-structure object. The two values are then said to be *re-entrant* or *token identical* or *structure shared*.

Based on these composite PRED values, Completeness and Coherence can be formulated as follows:

(4.11) *Completeness*
All arguments specified in a predicate's subcategorization frame are also realized in this predicate's f-structure.

(4.12) *Coherence*
Only those governable grammatical functions are realized in a predicate's f-structure that are specified as arguments in the predicate's subcategorization frame.

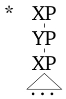
One further peculiarity about PRED values should be noted. Their values are by definition interpreted as *instantiated symbols*. This means that even if the same predicate, say ‘friend’, is introduced twice in a sentence, the two instances will be distinct f-structure objects ‘friend’$_1$ and ‘friend’$_2$ and thus cannot be unified. This reflects the resource sensitivity of language and excludes that arguments are doubled, inserting them simultaneously in several c-structural position where they may occur alternatively. An example would be the following ungrammatical German sentence with the subject both in the preverbal *Vorfeld* position, and in the *Mittelfeld*:

[7] Implementations of LFG parsers like the Xerox Grammar Writer's Workbench (Kaplan and Maxwell 1996) and the Xerox Linguistic Environment (XLE) implement composite PRED values along these lines.

(4.13) *Mein Freund ist heute mein Freund angekommen
my friend is today my friend arrived

The language generated by an LFG grammar can be defined as the set of c-structure/f-structure pairs, such that the c-structure is generated by the context-free grammar and the f-structure is the corresponding minimal model for the f-descriptions, satisfying Completeness and Coherence. There is however one proviso in the definition (Kaplan and Bresnan 1982, 266): Only those c-structures are considered which do not contain recursive non-branching dominance chains, as illustrated in (4.14).

(4.14) *Offline Parsability*



This restriction, commonly known as *offline parsability*, ensures that for a given string there are only finitely many c-structure analyses and thus the parsing task for LFG grammars is decidable (i.e., a procedure can be devised for the task which terminates after a finite number of steps). Quite obviously, since without this restriction a context-free grammar may predict an infinite number of analyses for a single string, a procedure constructing f-structure models from c-structures could never stop. I will not come back to processing details until chapter 6, but it is worthwhile noting at this point that the standard LFG formalism has such a built-in restriction motivated by processing considerations.

(4.15) *Language generated by an LFG grammar*

The language $L(G)$ generated by an LFG grammar G is the set of c-structure/f-structure pairs $\langle T, \Phi \rangle$, such that

T is a tree generated by the context-free grammar in G – subject to offline parsability –, and

Φ is the minimal model satisfying all f-descriptions that arise from instantiation of the f-annotation schemata in G, and satisfying the Completeness and Coherence condition.

The *string language* $\mathcal{L}(G)$ generated by an LFG grammar can easily be defined as the set of terminal strings derived from the c-structures in the language $L(G)$.[8]

[8] Throughout this dissertation I deviate from the standard terminology of formal language theory, in which my *string language* is simply the *language*. This is to avoid clumsiness when referring to the set of analyses generated by a formal grammar – which is done much more frequently than reference to the string language. From the context, the usage should generally be obvious. Furthermore I use a typographical distinction.

It is straightforward to extend the formal model of c- and f-structure outlined in this section to include further levels of representation, such as a semantic structure projected from f-structure. If a graph structure similar to f-structure is assumed for this semantic structure, we would have further feature-logic descriptions annotated to the rules and lexicon entries.[9] A formally equivalent way of including such a semantic representation in the LFG structures would be to assume a special feature SEMANTICS in the f-structures.[10] Given this close formal relationship between the syntactic level of f-structure and the level of semantic structure, it suffices for most formal and computational purposes relevant to the present dissertation to just consider c-structure/f-structure pairs.

4.2 Optimality-Theoretic LFG – the overall architecture

In chapters 2 and 3, some general empirical and learning issues were discussed at a rather informal level. Defining an OT system in a formal framework such as LFG will allow us to state the issues and their consequences for the formal system in a more precise way. In particular, this will permit an investigation of computational procedures to model language processing within an OT system.

In this section, an abstract specification of the components of an OT system is given, based on the formal means of LFG introduced in sec. 4.1. This will provide the context for a more detailed discussion of the character of the input, *Gen* and the violable constraints in the remainder of this chapter.

4.2.1 Abstract formal specification

Candidates The candidate analyses that OT-LFG deals with are tuples of structures as known from LFG, i.e., pairs of c-structure and f-structure (and

[9] The situation changes if a special resource-sensitive logic is assumed to underlie semantic construction as in the glue-language approach of Dalrymple and colleagues (see Dalrymple et al. 1993; Dalrymple et al. 1997, the contributions in Dalrymple 1999, and Dalrymple 2001 as a textbook). Then the formal treatment of semantic construction is no longer a special case of f-structure construction. In the present dissertation I cannot go into this framework, since too little is known about generation from semantic structures – a crucial building block for an OT system.

[10] There are some technical issues I cannot go into here: in order to be able to express the sharing of information correctly and in a general way, either the overall feature geometry has to be changed, or a special restriction operator has to be assumed (Wedekind and Kaplan 1993).

as just mentioned possibly more levels of analysis) that are in a correspondence relation. All analyses satisfy certain basic inviolable principles, which we can assume to be encoded in an LFG grammar G_{inviol}; thus the set of all possible candidate analyses is defined as the structures generated by this grammar G_{inviol}. Sec. 4.3 contains a discussion of what principles are encoded in this grammar G_{inviol}.

(4.16) *Definition of possible candidates*
The set of possible candidates is defined as the language $L(G_{\mathit{inviol}})$ generated by a formal LFG-style grammar G_{inviol}.

There are some issues as to how closely the LFG-style grammars used in OT-LFG systems resemble standard formal LFG grammars (see the definition of the language generated by an LFG grammar (4.15)). In sec. 4.3, I discuss whether the Completeness and Coherence conditions apply. In sec. 4.6 and chapter 6 the issue is addressed whether the offline parsability clause should apply for the LFG-style grammars used in OT-LFG systems.

Index/Input With the candidate analyses being fully specified LFG analyses, an appropriate representation for the input in the OT sense is a partially specified representation of LFG analyses. This gives us the strictly non-derivational system I argued for in sec. 3.3.5.

For recasting Grimshaw's (1997) analysis within LFG Bresnan (2000, sec. 1.1) assumes as the input "a (possibly underspecified) feature structure representing some given morphosyntactic content independent of its form of expression". An example (that in English would have *I saw her* as its optimal realization) is given in (4.17).[11]

(4.17)
$$\left[\begin{array}{ll} \text{PRED} & \text{`see}(x,y)\text{'} \\ \text{GF}_1 & \left[\begin{array}{ll}\text{PRED} & \text{`PRO'}\\ \text{PERS} & 1 \\ \text{NUM} & \text{SG}\end{array}\right]_x \\ \text{GF}_2 & \left[\begin{array}{ll} \text{PRED} & \text{`PRO'}\\ \text{PERS} & 3\\ \text{NUM} & \text{SG}\\ \text{GEND} & \text{FEM}\end{array}\right]_y \\ \text{TNS} & \text{PAST}\end{array}\right]$$

[11] The status of the arguments x and y in the semantic form 'see(x,y)' will be discussed in sec. 4.3.2.

More generally, we may want to assume an input comprising a feature representation of the semantic content of an utterance (and potentially some further "pragmatic" clues, such as information structural status etc., cf. sec. 3.3.2). So, the input is defined as follows:

(4.18) *Definition of the* ***input***
The *input* is a member of the set of well-formed (partial) f-structures $\mathcal{F}$.

Note that contrary to the situation with derivational candidates assumed in some OT syntactic work (cf. the discussion in sec. 3.3.5), there is no issue at what point of a candidate derivation the input information is available. Both the candidates and the input are formal objects that we should think of as static (with information about all levels being available simultaneously). The relations between them are just a mathematic relations between formal objects. Two kinds of input-candidate relations are relevant for a formal OT system: (i) *Gen* – involving a relation between the input and a set of candidates –, and (ii) the faithfulness constraints – involving a relation between an individual candidate and the input.

Candidate generation We can now give the following general definition of the function *Gen*, depending on the grammar G_{inviol}:

(4.19) *Definition of* ***Gen***
$\mathit{Gen}_{G_{\mathit{inviol}}}$ is a function from the set of f-structures to the power set of the analyses (c-structure/f-structure pairs $\langle T, \Phi\rangle$) in $L(G_{\mathit{inviol}})$:

$$\mathit{Gen}_{G_{\mathit{inviol}}}\!:\!\mathcal{F} \mapsto \wp(L(G_{\mathit{inviol}}))$$

In other words, $\mathit{Gen}_{G_{\mathit{inviol}}}$ takes each input f-structure Φ_{in} to a set of candidate analyses, which are contained in G_{inviol}:
$\mathit{Gen}_{G_{\mathit{inviol}}}(\Phi_{in}) \subseteq \{\langle T, \Phi'\rangle | \langle T, \Phi'\rangle \in G_{\mathit{inviol}}\}$. Further restrictions will be discussed below.

Constraint marking The OT constraints come into play when the alternative candidate analyses in the $\mathit{Gen}_{G_{\mathit{inviol}}}$ image of a given input f-structure are evaluated. The function *marks* assigns counts of constraint violations to each member of the candidate set. There are different ways in which the counts of constraint violations can be captured formally: in sec. 2.1, a multiset of constraint violation marks was assumed – for instance $\{{}^*C^2,\ {}^*C^2,\ {}^*C^4\}$ for a candidate violating constraint C^2 twice and constraint C^4 once (compare the example (2.5) in sec. 2.1). An alternative, but equivalent way is to represent the number of violations that each constraint incurs as a natural number. I will adopt this representation in this definition.

The constraints $\mathcal{C}$ used in an OT system are given as a sequence $\langle C^1, C^2, \ldots, C^k\rangle$. So we can represent the violation counts for a particular candidate as a sequence of natural numbers: $\langle n^1, n^2, n^3 \ldots n^k\rangle : n^i \in \mathbb{N}_0$. So, assuming a constraint sequence $\langle C^1, C^2, C^3, C^4, C^5\rangle$ for the above example, the violation counts would be $\langle 0, 2, 0, 1, 0\rangle$.

An individual constraint $C^i \in \mathcal{C}$ is then defined as a function taking a pair of an input f-structure and an LFG analysis to a natural number. The function *marks* depends not only on the candidates, but on the input structure too, for the following reason: we do not only have markedness constraints (which are defined on the candidate structures alone) but also faithfulness constraints (which are defined relative to the input).[12])

(4.20) *Definition of **OT constraints***
$\mathcal{C}$: a sequence of constraints $\langle C^1, C^2, \ldots, C^k\rangle$;
for each constraint $C^i, i = 1..k$:

$$C^i(\Phi_{in}, \langle T, \Phi'\rangle) \in \mathbb{N}_0$$

The specification of markedness constraints based on LFG analyses is discussed in sec. 4.4. Faithfulness constraints are discussed in sec. 4.6.

For the function *marks*, which takes into account all constraints, we get:

(4.21) *Definition of **marks***
$\mathit{marks}_{\mathcal{C}}$ is a function from (input) f-structures and LFG analyses to a sequence of k natural numbers
(where $k = |\mathcal{C}|$, the size of the constraint set)

$$\mathit{marks}_{\mathcal{C}} : \mathcal{F} \times L(G_{\mathit{inviol}}) \mapsto \mathbb{N}_0^k, \text{ such that}$$

$$\mathit{marks}_{\mathcal{C}}(\Phi_{in}, \langle T, \Phi'\rangle) = \langle C^1(\Phi_{in}, \langle T, \Phi'\rangle), C^2(\Phi_{in}, \langle T, \Phi'\rangle), \ldots, C^k(\Phi_{in}, \langle T, \Phi'\rangle)\rangle$$

[12] In sec. 4.6 the input-dependence of *marks* will be eliminated, since under the definition of $\mathit{Gen}_{G_{inviol}}$ adopted in sec. 4.3.1 the relevant faithfulness constraints can be defined on the candidate structures alone.

Harmony evaluation The key concept of optimization – harmony evaluation in the narrow sense – depends on the constraint violation counts for each input/candidate pair from a given candidate set $\mathit{Gen}_{G_{inviol}}(\Phi_{in})$, and on the language specific constraint ranking over the constraint set $\gg_{\mathcal{L}}$. The function *Eval* formalizing this concept determines the most harmonic candidate according to definition (2.3), repeated here.

(2.3) Candidate A_i is more harmonic than A_j ($A_i \succ A_j$) if it contains fewer violations for the highest-ranked constraint in which the marking of A^i and A^j differs.

(4.22) *Definition of **Eval***
Given a set of LFG analyses Γ,

$$\mathit{Eval}_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(\Gamma) = \{ \langle T_j, \Phi_j\rangle \in \Gamma \mid \langle T_j, \Phi_j\rangle \text{ is maximally harmonic for all analyses in } \Gamma\text{, under ranking } \gg_{\mathcal{L}} \}$$

Note that this definition is compatible both with a classical, strict constraint ranking and with a stochastic constraint ranking as assumed by Boersma (1998). As discussed briefly in sec. 3.3.1, the latter model is superior from the perspective of learnability, and it also constitutes an interesting mechanism for deriving optionality and frequency effects.

Language generated by an OT-LFG system

An OT-LFG system is specified by three components.

(4.23) *Definition of an OT-LFG system*
An OT-LFG system $\mathcal{O}$ is defined as $\langle G_{inviol}, \langle \mathcal{C}, \gg_{\mathcal{L}}\rangle\rangle$, where

G_{inviol} is a formal LFG-style grammar defining the possible candidate analyses,

$\mathcal{C}$ is a sequence of OT constraints, and

$\gg_{\mathcal{L}}$ is a ranking over $\mathcal{C}$.

Finally, the language generated by an OT-LFG system can be defined as the set of analyses $\langle T_j, \Phi_j\rangle$ for which there exists an input f-structure Φ_{in} such that $\langle T_j, \Phi_j\rangle$ is among the most harmonic candidates for that input (i.e., $\mathit{Eval}_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(\mathit{Gen}_{G_{inviol}}(\Phi_{in}))$).

(4.24) *Definition of the language generated by an OT-LFG system $\mathcal{O} = \langle G_{inviol}, \langle \mathcal{C}, \gg_{\mathcal{L}} \rangle \rangle$*

$$L(\mathcal{O}) = \{\langle T_j, \Phi_j \rangle \in G_{inviol} \,|\, \exists \Phi_{in} : \langle T_j, \Phi_j \rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(Gen_{G_{inviol}}(\Phi_{in}))\}$$

The string language $\mathcal{L}(\mathcal{O})$ generated by an OT-LFG system can be defined accordingly as the set of terminal strings for such analyses $\langle T_j, \Phi_j \rangle$.

An example of a linguistic OT-LFG system satisfying this definition will be developed in the subsequent sections (specifically in sec. 4.3 and 4.4) which will focus on the concrete specification of the components.

4.2.2 Degrees of freedom in this OT-LFG architecture

Based on the definitions just presented, there are three essential components specifying a particular OT-LFG system: the "base grammar" G_{inviol}, the OT constraints $\mathcal{C}$, and the constraint ranking $\gg_{\mathcal{L}}$. The formalization leaves these components open to be filled out by empirical and conceptual linguistic work. Recall that by assumption of the linguistic OT approach, the former two are universal, and only the latter is language-specific. So, it is a goal for linguistic research to determine the specification of the former two (G_{inviol} and $\mathcal{C}$) in such a way that the language-specific ranking $\gg_{\mathcal{L}}$ is learnable based on language data.

Note however that in addition there are some further degrees of freedom in this OT-LFG architecture, on a more technical level:

(4.25) *Degrees of freedom in the definitions* (4.16)–(4.24)

a. The definition of possible candidates is based on the language generated by a "formal LFG-style grammar G_{inviol}"; this leaves open whether G_{inviol} is interpreted as an LFG grammar in the strict sense or whether the Completeness and Coherence condition is modified and/or the offline parsability condition is loosened up.

b. The exact specification of the function $Gen_{G_{inviol}}$ is left open.

c. It has not been fixed how the constraints are formally specified, given the input and a candidate structure.

For clarification of the last two points note that the definitions (4.19) and (4.20) given above specify only what kind of function $Gen_{G_{inviol}}$ is (mapping an f-structure to a set of candidates) and what kind of function a constraint is (mapping a candidate analysis to a natural number). This leaves completely open how the functions are specified. For example, the function $Gen_{G_{inviol}}$ may be a constant function that assigns the same candidate set to all possible input f-structures; or it may assign different candidate sets to different f-structures, based on some structural relationship. Likewise for the constraints, there is a wide spectrum of possibilities: the numbers they assign to candidate structures may be based on the counting of simple structural patterns, or they may involve complicated conditions (for instance, it is conceivable to formulate a constraint as a context-free grammar, assigning 0 when the candidate c-structure is included in the language and 1 otherwise).

All three aspects listed in (4.25) have to be pinned down to complete the formal specification of an OT-LFG system. The choices do not seem to have as clear an empirical impact as variations of the main components of the OT-LFG system have. But (i) they *do* have significant impact on the processing complexity of the formal system (as I show in sec. 4.2.3), and (ii) the basic assumptions of the OT approach discussed in chapter 2 and the empirical and conceptual observations of chapter 3 may be reflected more or less adequately in the formalization, depending on these choices.

As an example for point (ii) note that a system relying on LF-unfaithful candidates as discussed in sec. 3.3.3 is compatible with the definitions. There need not be any structural connection between the input/Index that $Gen_{G_{inviol}}$ takes as its arguments and the set of candidates it assigns to this input. In sec. 3.3.4, I argued that this circumstance is undesirable from the point of view of learnability.

4.2.3 Undecidability arguments for unrestricted OT systems

To see the impact of the choices in (4.25) on the processing complexity, let us look at two non-linguistic examples of OT systems both of which allow the construction of an undecidability argument (they can be seen as a variant of the sketch of an undecidability argument for unrestricted OT systems that Johnson (1998) presents).

Undecidability due to powerful constraints

(4.26) *A constructed OT-LFG system (schema) $\mathcal{O}_1$*

Let G_1 and G_2 be context-free grammars.
G_1 has the starting symbol S_1.

Specify the c-structure part of G_{inviol} by adding the following productions to G_1:
$\mathrm{S} \to \mathrm{S}_1$
$\mathrm{S} \to$ *yes*,

where S is a new symbol, used as the start symbol of G_{inviol} and *yes* is a new terminal symbol. (The f-annotations in G_{inviol} are irrelevant. We may assume arbitrary f-structures.)

Define $Gen_{G_{inviol}}$ as follows:
$Gen_{G_{inviol}}(\Phi) = L(G_{inviol})$, for all Φ

Assume two constraints:

$C^1(\Phi, \langle T, \Phi' \rangle) =$ 0 if the terminal string of T is in $\mathcal{L}(G_2) \cup$ {*yes*}
1 otherwise

$C^2(\Phi, \langle T, \Phi' \rangle) =$ 1 if the terminal string of T is *yes*
0 otherwise

Assume the ranking $C^1 \gg_{\mathcal{L}} C^2$.

Note that $Gen_{G_{inviol}}$ is a constant function, assigning the full set of possible candidates to any input; C^1 is a constraint based on the context-free language G_2.

The system works fine if we assume simple grammars for G_1 and G_2. For example, we may assume $\mathcal{L}(G_1) = \{a, aa\}$ and $\mathcal{L}(G_2) = \{b, c\}$. The possible candidate strings generated by G_{inviol} are then $\{a, aa, yes\}$. Now, let us check whether the string *yes* is in the string language generated by the OT-LFG system. According to the definition there has to be some input such that *yes* is the terminal string of the optimal analysis from the candidate set assigned to that input by $Gen_{G_{inviol}}$. Since all candidate sets are the same (and the input plays no role) this is easy to check, we need only look at one tableau:

(4.27)

Input: (arbitrary)	C^1 "$\in \mathcal{L}(G_2) \cup$ {*yes*}?"	C^2 "**yes*"
a. a	*!	
b. aa	*!	
c. ☞ *yes*		*

So, *yes* is indeed in the string language. In fact, it is the only string in that language. If we change G_2 from the previous example to make $\mathcal{L}(G_2) = \{a, b, c\}$, we get the following tableau:

(4.28)

Input: (arbitrary)	C^1 "$\in \mathcal{L}(G_2) \cup$ {*yes*}?"	C^2 "**yes*"
a. ☞ a		
b. aa	*!	
c. *yes*		*!

The string *yes* is no longer in the language generated (instead, all strings that are in the intersection of the two languages are, since they all have the same constraint profile). The only way *yes* can ever win is that all other candidates fail to satisfy C^1. So what the OT-LFG system schema $\mathcal{O}_1$ in (4.26) effectively does is check whether the intersection of two context-free languages is empty. This problem is known to be undecidable in the general case; so the recognition problem for unrestricted OT-LFG systems (checking whether a certain string is in the string language) is also undecidable in the general case.

Since the formal system used for this argument contained an unnecessarily powerful constraint, it is worthwhile to investigate more restricted definitions.

Undecidability due to powerful candidate generation

This second type of undecidability argument was suggested to me by Jürgen Wedekind (p.c.). It exploits the fact that the emptiness problem for an LFG language is known to be undecidable[13] and uses a powerful G_{inviol} in candidate generation. This system can be constructed as follows:

(4.29) *Another constructed OT-LFG system (schema) $\mathcal{O}_2$*

Assume an LFG grammar G_1 with start symbol S_1, for which the problem $\mathcal{L}(G_1) = \emptyset$ is undecidable.

Construct from G_1 the grammar G_{inviol} with the new start symbol S, a new nonterminal symbol Y and the new terminal symbol *yes*. The following productions are added to the productions of G_1:

S → Y
(↑PRED)=‘yes’
S → S_1
(↑CHECK)=+
(↑PRED)=‘yes’
Y → *yes*

Assume a single constraint:

$C^1(\Phi, \langle T, \Phi' \rangle) =$ 0 if Φ' has the feature [CHECK +]
1 otherwise

The candidate *yes* violates the constraint C^1 (since its f-structure does not contain the feature [CHECK +]). Analyses making use of the rule S → S_1 satisfy C^1. But we can nevertheless get *yes* as the optimal candidate for Φ_{in} =[PRED ‘yes’]: there may be no other candidates in the candidate set. This

[13] According to the introduction to part V in Dalrymple et al. (1995, 333), this was first shown in 1983 by Kelly Roach.

is the case iff no candidates can be derived with the S_1 symbol, i.e., when $\mathcal{L}(G_1) = \emptyset$. Since by assumption this problem is undecidable it is also undecidable whether *yes* $\in \mathcal{L}(\mathcal{O}_2)$.

What is unintuitive about this OT system is that there is no structural relationship between the f-structure constructed in the original LFG grammar G_1 (i.e., $\phi(S_1)$) and the f-structure projected from the new start symbol, i.e., $\phi(S)$. S is always mapped to the f-structure
$\begin{bmatrix} \text{PRED} & \text{`yes'} \\ \text{CHECK} & + \end{bmatrix}$
– no matter what $\phi(S_1)$ is like. But in a linguistic grammar, this ignored part of the structure reflects the candidate's interpretation. The intuition that all candidates should have the same underlying interpretation, modelled by the semantic part of f-structure, is failed.

The two undecidability arguments motivate that both the expressive power of individual constraints and the expressive power of candidate generation have to be suitably restricted.[14]

4.2.4 Fixing the choices in the definitions

An objective of this dissertation is to arrive at a formalization of OT syntax that is sufficiently restricted to permit realistic processing, while at the same time meeting the assumptions and intuitions underlying the theoretical OT approach. Further details of processing complexity will not be discussed until chapter 6; the strategy I adopt is to first fix the degrees of freedom mentioned in (4.25) in a way compatible with the empirical and conceptual criteria noted in the previous chapters and show afterwards that the resulting system is also adequate for processing.

Point (4.25a) – addressing the freedom of candidate generation based on G_{inviol} – is relevant for the treatment of unfaithful candidates. I will come back to it briefly in sec. 4.3 and sec. 4.6 and particularly in chapter 6. For the moment, the decision is not of crucial relevance.

The points (4.25b) and (4.25c) – the exact specification of $Gen_{G_{inviol}}$ and the individual constraints – appear to be antagonistic. If $Gen_{G_{inviol}}$ goes a long way in restricting the possible candidate structures to the observable language data, then the constraints need not be highly expressive, since they only have

[14] I will discuss a third undecidability argument, related to the second one presented here, in sec. 6.3.1: ensuring that the f-structure is considered for all candidates alone does not suffice to guarantee decidability of the recognition problem for OT-LFG systems (without offline parsability). F-structure must furthermore be related to the surface string, or possibly a context representation.

to control comparatively small choices. However, this goes against the methodological principle of the OT approach (3.1), discussed in sec. 3.2.1 and repeated here for convenience.

(3.1) *Methodological principle of OT*
Try to explain as much as possible as an effect of constraint interaction.

Prima facie this principle would suggest a maximally general and unrestricted $Gen_{G_{inviol}}$. But as we have seen in sec. 4.2.2 (and sec. 3.3.2), when applied in syntax, such a concept of $Gen_{G_{inviol}}$ leads to problems both with learnability considerations and with decidability.

For the standard conception of OT phonology the learnability and decidability problem with a weak $Gen_{G_{inviol}}$ do not pose themselves. Learnability is not negatively affected if all candidate sets are identical and just the input differs: the candidate analyses do not *contain* a "deep", interpreted level of representation that may differ from the input (like LF or the f-structure in syntax); rather the interface to the rest of the linguistic and cognitive system is concentrated in the input. So inferences from the utterance context permit direct conclusions about the input.[15]

The decidability problem does not arise either (if regular languages and relations are assumed for modelling $Gen_{G_{inviol}}$ and the constraints, cf. Ellison 1994; Frank and Satta 1998; Karttunen 1998): regular languages are closed under intersection, so formally it makes no difference when certain restriction are moved from $Gen_{G_{inviol}}$ to the constraint space. Following insights of (Frank and Satta 1998) and (Karttunen 1998), the entire OT system can be implemented as a single finite-state transducer implementing $Gen_{G_{inviol}}$ and the constraints composed by "lenient" composition (in Karttunen's terminology).[16]

However for OT syntax, where the candidate structures contain their own level of interpretation and regular languages are too unexpressive for modelling the data, a setup has to be found that makes $Gen_{G_{inviol}}$ slightly stronger without taking too much of the explanatory burden away from constraint interaction, so (3.1) is still met. (The criterion for deciding what should definitely follow

[15] As pointed out in footnote 14 on page 42, such inferences from utterance context may indeed be required for phonological OT systems, since surface forms *can* be ambiguous (cf. Hale and Reiss 1998 for the ambiguity problem posed by a simple strong bidirectional OT system not making use of information from the utterance context in the determination of the underlying form). But if the inferences work properly, they suffice to determine the underlying input. This is *not* guaranteed for unrestricted OT syntax systems, in which LF and the input may differ. (Note that all contextual inferences can provide only information about the candidate's actual LF, and thus not necessarily about the input which may not be faithfully rendered at LF.)

[16] However for multiple violations of a single constraint a fixed upper bound has to be assumed.

as an effect of constraint interaction is crosslinguistic comparison, as was done for the syntactic MAX-IO and DEP-IO violations in sec. 3.2.3.)

The setup I propose uses (formally) very simple individual constraints (discussed in sec. 4.4) and a conception of $Gen_{G_{inviol}}$ that disallows divergences at the level of the interpreted part of the candidate structures, i.e., the part of f-structure that corresponds to the input (sec. 4.3). (Translated to the Chomskyan terminology, this covers both the predicate-argument structure at d-structure and the interpretation-relevant aspects of LF.)

Although this may sound like a massive restriction, this $Gen_{G_{inviol}}$ conception is compatible with a view that keeps up maximal generality at the surface level of syntax, as will be discussed in sec. 4.6.[17]

4.3 Candidate generation and the inviolable principles

4.3.1 The restricted definition of $\boldsymbol{Gen_{G_{inviol}}}$

Based on the considerations of sec. 4.2.4, the candidate generation function $Gen_{G_{inviol}}$ is defined as follows:

(4.30) *Restricted definition of* ***Gen***

$$Gen_{G_{inviol}}(\Phi_{in}) = \{ \langle T, \Phi' \rangle \in L(G_{inviol}) \mid \Phi_{in} \sqsubseteq \Phi', \text{ where } \Phi' \text{ contains no more semantic information than } \Phi_{in} \}$$

So only those of the possible candidate analyses in $L(G_{inviol})$ are picked whose f-structure is *subsumed* by the input f-structure, and which do not add any semantically relevant information. There is some leeway for the exact definition of *semantic information*. But note that in every concrete formulation of G_{inviol}, this can be specified by declaring particular features or feature combinations as contributors to semantic information.[18]

[17] So the stronger $Gen_{G_{inviol}}$ restrictions in a comparison with the OT phonology model may be viewed as no more than a compensation for the different type of representations used in syntax. A totally different formalization of OT syntax might attempt to use only the surface form as candidates and use more expressive constraints, circumventing the decidability problem addressed in sec. 4.2.2 in a different way.

[18] The qualification "where Φ' contains no more semantic information than Φ_{in}" could be expressed more formally as follows:

$$\Phi' |_{F_{sem}} \sqsubseteq \Phi_{in}$$

where $\Phi' |_{F_{sem}}$ is defined as the largest f-structure $\Phi'' \sqsubseteq \Phi'$, such that all features contained in its path are members of F_{sem} (the set of semantic features).

This formalization meets the intuition of Bresnan's (2000) original account of candidate generation in OT-LFG: at an abstract level, $Gen_{G_{inviol}}$ is indeed generation from the input with an LFG grammar. The candidate analyses can be viewed as being *generated* from the input structure by monotonically adding (non-semantic) information. Conveniently, the task of computing $Gen_{G_{inviol}}(\Phi_{in})$ is then exactly the classical task of generation from an underspecified f-structure, given an LFG grammar (G_{inviol}). Processing is discussed further in chapter 6.

4.3.2 Completeness and Coherence in OT syntax

There is an alternative way of stating the restricting condition in candidate generation, drawing a parallel to the standard LFG concepts of Completeness (4.11) and Coherence (4.12).[19] What we want to implement is that candidates may contain neither more nor less semantic information than specified in the input. We could assume a special place in the f-structure for encoding the input information, e.g., within the composite PRED values (compare (4.10)). The input (4.17) would then look roughly as follows (note that all input information has to be coded into the structures under PRED – here I use *ad hoc* feature names like REF-NUM for the semantic referent's number specification etc.):

(4.31) *Potential way of re-coding the OT input*

$$\left[\begin{array}{ll} \text{PRED} & \left[\begin{array}{ll} \text{FUNCTOR} & \text{see} \\ \text{TNS} & \text{PAST} \\ \text{ARGUMENT1} & \left[\begin{array}{ll} \text{PRED} & \left[\begin{array}{ll} \text{FUNCTOR} & \text{PRO} \\ \text{REF-PERS} & 1 \\ \text{REF-NUM} & \text{SG} \end{array}\right] \end{array}\right] \\ \text{ARGUMENT2} & \left[\begin{array}{ll} \text{PRED} & \left[\begin{array}{ll} \text{FUNCTOR} & \text{PRO} \\ \text{REF-PERS} & 3 \\ \text{REF-NUM} & \text{SG} \\ \text{REF-GEND} & \text{FEM} \end{array}\right] \end{array}\right] \end{array}\right] \end{array}\right]$$

Then we can express restricted candidate generation through Completeness and Coherence conditions:

(4.32) *OT-Completeness*
All information specified as a predicate's input information (= under PRED) is also realized in this predicate's f-structure.

[19] Compare also Wedekind's (1995) terminology in his discussion of generation.

(4.33) *OT-Coherence*
Only the semantic information that is specified as a predicate's input information (= under PRED) is also realized in this predicate's f-structure.

This would permit us to move the subsumption restriction on $Gen_{G_{inviol}}$ into the formal specification of the underlying LFG-style grammar, i.e., into the definition of possible candidate structures in general (4.16). Candidates with an over- or under-informative f-structure would be incoherent or incomplete and thus no longer exist in G_{inviol}, so they would not have to be excluded in the definition of $Gen_{G_{inviol}}$.[20] However, I will keep to definition (4.30), assuming it to be more perspicuous. We may think of the OT-Completeness and OT-Coherence conditions to be (redundantly) at work within G_{inviol} nevertheless.

It is interesting to note a change in the source of the reference information for checking Completeness/Coherence. In classical LFG, this information is contributed by the *lexicon entries* of the predicates (i.e., the verbs, prepositions etc.). The PRED value with the subcategorization frame is conveniently written in one line, using angle brackets as in (↑PRED)='devour⟨(↑SUBJ) (↑OBJ)⟩' (compare (4.10)). In OT-LFG, the relevant reference information is contributed by the *input*. This means that if we nevertheless assume subcategorization frames in the lexicon entries then they are pretty much redundant. Only those matching the input will be usable (since they have to be unified with the input). The only interesting case arises when we look at pathological inputs like a strictly transitive verb such as *devour* used with just a single argument. Here, a lexicon lacking (↑PRED)='devour⟨(↑SUBJ)⟩' would lead to an empty candidate set, predicting that the input cannot be expressed in any language. It is questionable however whether such an approach would be in the spirit of OT. For instance, OT phonology will predict a surface realization for any underlying nonsense string of phonemes. The learner will just never come across such a string and thus it will not be entered into the inventory of underlying forms. Of course, the situation is slightly different in syntax, since we are not dealing with finite lists of underlying forms. However, we have to assume that the inputs are processed further in the conceptual cognitive system, and this further processing detects and excludes nonsense inputs. The syntactic system itself will be more perspicuous and general if it does not attempt to anticipate such conceptual restrictions.

In other words, it seems most adequate for the OT syntax setup to assume lexicon entries without a specification of the subcategorization frame, compatible with all underlying argument combinations. Lexical preferences may then

[20] We would get

(i) $Gen_{G_{inviol}}(\Phi_{in}) = \{\ \langle T, \Phi' \rangle \in L(G_{inviol}) \mid \Phi_{in}$ is the input information of $\langle T, \Phi' \rangle\ \}$

be derived through constraint interaction. For example, the thought of someone eating very fast, leaving unexpressed what he eats, would turn out in English as *he was eating hastily* or something similar (note that the input would certainly contain no particular lexical items, like English *devour*, but a more abstract conceptual representation). The verb *devour* would not be used because it is suboptimal for expressing this thought. Such a constraint-based account is essential if we want to have a uniform learning theory for syntax and the lexicon. It also bears much more explanatory potential for argument frame variation in the lexicon. Of course, this type of account presupposes the assumption of rather fine-grained constraints which are sensitive to individual lexical items – an issue which I cannot pursue any further in this dissertation.

In the representation of OT analyses, I will not use angle brackets which would suggest a subcategorization frame that is checked within the formal system of LFG. Rather I will use parantheses following the semantic form in the PRED value of input f-structures. For example, we would get [PRED 'devour(x, y)']. This notation is suggestive for the interpretation of dependents as semantic arguments, without the standard LFG mechanism of Completeness and Coherence being at work.

4.3.3 The base grammar G_{inviol}

In this subsection, an impression of the kinds of inviolable principles encoded in G_{inviol} should be given. As an example, assume we want to encode Grimshaw's (1997) fragment of inversion data in English in OT-LFG, following the reconstruction by Bresnan (2000, sec. 2). The formal LFG-style grammar G_{inviol} will have to formalize a theory of extended projections. This can be done on the basis of LFG's extended head theory that Bresnan (2001, ch. 7) discusses in detail. The principles Bresnan assumes can be fleshed out in a set of LFG rules, i.e., context-free rules[21] with f-annotations. (Kuhn 1999b) contains a more detailed discussion of how extended head theory can be captured in concrete rule formulations; here it may suffice to assume that the effect of the principles can be envisaged as a set of classical LFG rules like the rules in (4.34),[22] generating X-bar-configurations with an extension to functional categories (like the verbal functional categories I and C). A lexical category and the corresponding functional categories on top of it form an *extended projection* (Grimshaw 1991; Bresnan 2001). (I do not actually assume a fixed limitation to a maximum

[21] More precisely, a generalization of context-free rule notation which allows regular expressions on the right-hand side, cf. footnote 4 on page 55.

[22] DF is a generalization over discourse functions (TOPIC, FOCUS, Q-FOCUS and SUBJECT); CF generalizes over complement functions (OBJ, OBL$_\theta$, COMP etc.). The non-endocentric category S that Bresnan (2000, 2001) assumes is ignored here.

of two functional categories, so G_{inviol} really generates arbitrarily many FP's within an extended projection.)

(4.34) *Some of the rules in* G_{inviol}

$$\begin{array}{lcccc}
\text{CP} & \longrightarrow & (\text{XP}) & (\text{C}') \\
 & & (\uparrow\textsc{df}){=}\downarrow & \uparrow{=}\downarrow \\
\text{C}' & \longrightarrow & (\text{C}) & (\text{IP}) \\
 & & \uparrow{=}\downarrow & \uparrow{=}\downarrow \\
\text{IP} & \longrightarrow & (\text{XP}) & (\text{I}') \\
 & & (\uparrow\textsc{df}){=}\downarrow & \uparrow{=}\downarrow \\
\text{I}' & \longrightarrow & (\text{I}) & (\text{VP}) \\
 & & \uparrow{=}\downarrow & \uparrow{=}\downarrow \\
\text{VP} & \longrightarrow & \text{V}' & \\
 & & \uparrow{=}\downarrow & \\
\text{V}' & \longrightarrow & (\text{V}) & (\text{XP}) \\
 & & \uparrow{=}\downarrow & (\uparrow\textsc{cf}){=}\downarrow
\end{array}$$

There are two crucial points to note about (4.34): first, the ↑=↓ annotation of both the C and the IP category in the C′ rule, and the I and the VP in the I′ rule. The functional head and its complement (in c-structure) act as "co-heads" on f-structure, i.e., their f-structures are identified. (All categories of an extended projection are thus mapped to the same f-structure.) Second, all categories are optional. These points together ensure that a given input f-structure has a wide range of realization alternatives – as required in an OT account with a weak $Gen_{G_{inviol}}$ component and strong effects of constraint interaction (sec. 4.2.4): since the f-structures of all heads within the extended projection are identified, each of them is a potential site for a category realizing information from the input f-structure. The structures generated for the underspecified input f-structure in (4.35) include the LFG analyses in (4.37) on page 77, for example.

(4.35)
$$\left[\begin{array}{ll}
\textsc{pred} & \text{‘read}(x,y)\text{’} \\
\textsc{gf}_1 & \left[\begin{array}{ll}\textsc{pred} & \text{‘}\textsc{pro}\text{’}\end{array}\right]_x \\
\textsc{gf}_2 & \left[\begin{array}{ll}\textsc{pred} & \text{‘}\textsc{pro}\text{’} \\ \textsc{op} & \textsc{q}\end{array}\right]_y \\
\textsc{tns} & \textsc{fut}
\end{array}\right]$$

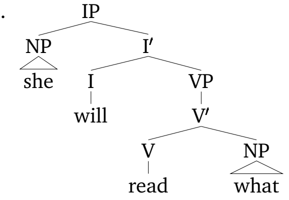
The grammar specification given in (4.34) is not totally sufficient for deriving analyses (4.37b) and (4.37c). The f-annotation of the specifier XP in the CP rule will introduce the f-structure for *what* only under a discourse function, i.e. Q-FOCUS. The fact that the value of the Q-FOCUS feature and the grammatical function OBJ are token identical (or re-entrant/structure-shared) follows from an additional f-annotation not shown in (4.34). There are different ways of achieving the effect. Bresnan (2001) assumes an inside-out functional-uncertainty introduced by a phonologically empty object NP (or DP) under V′. I assume here an outside-in functional-uncertainty equation as an additional f-annotation in the CP rule (Kaplan and Zaenen 8995, 154):[23]

(4.36)
$$\begin{array}{lccc}
\text{CP} & \longrightarrow & (\text{XP}) & (\text{C}') \\
 & & (\uparrow\textsc{df}){=}\downarrow & \uparrow{=}\downarrow \\
 & & (\uparrow\textsc{df}){=}(\uparrow\{\textsc{comp}\mid\textsc{xcomp}\}^{*}\ (\textsc{gf}\text{–}\textsc{comp})) &
\end{array}$$

where the two instances of DF are the same (i.e., both TOPIC or both Q-FOCUS, etc.) and GF: the grammatical functions.

The regular expression in the feature path expression in (4.36) (note the operations disjunction "{ | }", Kleene star "*" and complementation "–") allows one to cover arbitrary long-distance dependencies between the topicalized argument and the verb introducing the f-structure predicate.

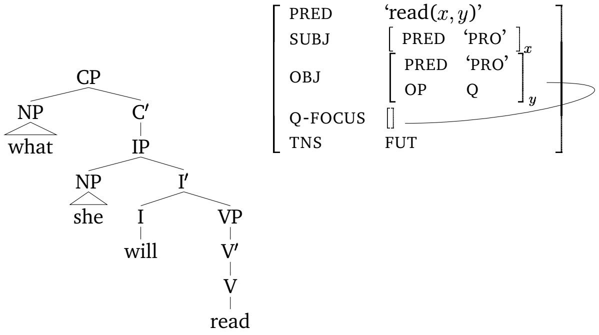
(4.37) a.



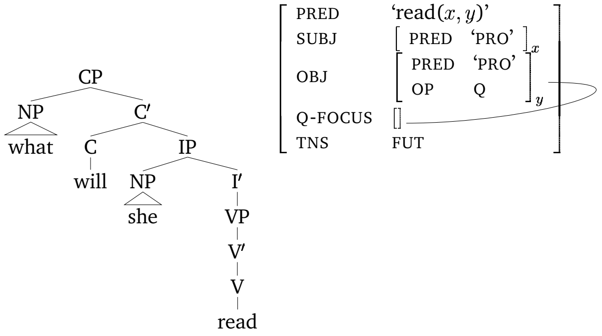
$$\left[\begin{array}{ll}
\textsc{pred} & \text{‘read}(x,y)\text{’} \\
\textsc{subj} & \left[\begin{array}{ll}\textsc{pred} & \text{‘}\textsc{pro}\text{’}\end{array}\right]_x \\
\textsc{obj} & \left[\begin{array}{ll}\textsc{pred} & \text{‘}\textsc{pro}\text{’} \\ \textsc{op} & \textsc{q}\end{array}\right]_y \\
\textsc{tns} & \textsc{fut}
\end{array}\right]$$

[23] The main reason for adopting the outside-in functional-uncertainty approach is presentational: the freedom of $Gen_{G_{inviol}}$, providing all kinds of candidate analyses is brought out clearer with this variant (without having to go into great technical detail). In (Kuhn 2001a, 335) I present essentially the same fragment, but based on the inside-out functional-uncertainty specification.

b.



c.



Many further aspects of the non-derivational framework of LFG play a role in its use as the base formalism of an OT system. I cannot go into the details here (see Bresnan 2001). Note however the differences between the representations in (4.37) and the corresponding ones in (2.6), sec. 2.1, which are set in the GB-based system used by Grimshaw (1997): In the c-structures in LFG, all elements are "base-generated" in their "final" position. No movements or chains are assumed; the kind of information captured by these concepts in GB-style approaches is available in LFG's f-structures and the correspondence mapping. The OT constraints can be straightforwardly specified by referring to (c- or f-)structural configurations (see sec. 4.4).

To close this section, it should be noted that although the resulting grammar is formally an LFG grammar, it is certainly unusual since it "overgenerates" vastly, producing all universally possible c-structure-f-structure pairings. This is due to the special role that this LFG grammar plays as part of an OT model: given the different definition of grammaticality, the set of analyses generated by the LFG grammar is not the set of *grammatical* analyses of a particular language (as classically assumed). Rather, it is the union over all possible candidate sets – for any input.

4.4 The violable constraints: markedness constraints

According to the formalization in sec. 4.2, a constraint is generally a function mapping an input/candidate pair to a natural number (4.20). OT distinguishes two major types of constraints: faithfulness and markedness constraints. Markedness constraints are checked on the candidate analysis alone, independent of the underlying input. Faithfulness constraints are violated when the surface form diverges from the underlying form (empirical examples from phonology and syntax were discussed in sec. 3.2). For this reason, the formalization apparently has to rely on a comparison of the input and the candidate analysis. It turns out that with the conception of candidate generation introduced in sec. 4.3, it is redundant to check the candidate analysis against the input; so even for faithfulness constraints, a consideration of just the candidate analysis suffices. This point will be discussed in more detail in sec. 4.6. For the time being, I will put faithfulness constraints aside and concentrate on markedness constraints. The objective is to establish a concrete way of specifying a constraint as an instance of the following restricted definition:

(4.38) *Restricted definition of an OT constraint*
Each constraint $C^i \in \mathcal{C}$ is a function, such that

$$C^i(\langle T, \Phi \rangle) \in \mathbb{N}_0$$

In sec. 4.4.1, the formulations of markedness constraints used in OT-LFG are reviewed, to provide a basis for discussion of the precise formalization. Sec. 4.4.2 addresses the universally quantified character of constraints, coming to the conclusion that this should *not* be reflected in the individual constraints. Sec. 4.4.3 introduces the formalization of OT constraints as constraint schemata. Finally, in sec. 4.4.4 I point out that the standard LFG means of expression are sufficient to specify OT constraints in accordance with the assumptions behind OT.

4.4.1 Markedness constraints in OT-LFG

In most OT work the constraints are formulated in prose. However, it seems to be a central assumption that the constraints can be formalized as structural descriptions of the type of representations output by $Gen_{G_{inviol}}$ – i.e., LFG structures in our case. As a set of sample constraints, let us again look at an adaptation of the constraints that Bresnan (2000, sec. 2) uses in her illustrative reconstruction of Grimshaw's (1997) fragment (parts of which I sketched in sec. 2.1). Due to their original illustrative purpose, these specific constraints do not necessarily play a role in original OT-LFG accounts (viewing OT-LFG as a theoretical paradigm, rather than just a formalism). But the means of expression used in these constraints can be regarded as representative.

The constraints involved in the derivation of *What will she read*, which was also used for illustration in sec. 2.1, involves the constraints in (4.39) to be discussed in the following. The tableau for the sample candidates from (4.37), based on these constraints, is anticipated in (4.40).

(4.39) a. Op-Spec (Bresnan 2000)
An operator must be the value of a DF [discourse function] in the f-structure.

b. Ob-Hd (Bresnan 2000, (21))
Every projected category has a lexically filled [extended, JK] head.

c. Dom-Hd (Bresnan's (2000) Stay (24))
Categories dominate their extended heads.

d. Arg-as-CF
Arguments are in c-structure positions mapping to complement functions in f-structure.

(4.40)

Input: $\begin{bmatrix} \text{PRED} & \text{`read}(x,y)\text{'} \\ \text{GF}_1 & \begin{bmatrix}\text{PRED} & \text{`PRO'}\end{bmatrix}_x \\ \text{GF}_2 & \begin{bmatrix}\text{PRED} & \text{`PRO'} \\ \text{OP} & \text{Q}\end{bmatrix}_y \\ \text{TNS} & \text{FUT}\end{bmatrix}$	Op-Spec	Ob-Hd	Arg-as-CF	Dom-Hd
a. $[_{\text{IP}}$ she will $[_{\text{VP}}$ read what$]]$	*!			
b. $[_{\text{CP}}$ what $[_{\text{IP}}$ she will $[_{\text{VP}}$ read$]]]$		*!	*	
c. ☞ $[_{\text{CP}}$ what will $[_{\text{IP}}$ she $[_{\text{VP}}$ read$]]]$			*	*

(4.39a) Op-Spec and (4.39b) Ob-Hd are correspondents to Grimshaw's constraints with the same name (cf. (2.1)), now based on the LFG representations.

Since in G_{inviol} (cf. (4.34)) the only way of introducing something under a discourse function is as the specifier of CP or IP (and since the specifier of VP is never filled), (4.39a) amounts to the same as (2.1a) "Syntactic operators must be in specifier position". (4.39b) relies on a slightly more complicated reconstruction on the placement of lexical and functional X^0 heads within extended projections. The concept of the *extended head* is defined to accomodate for the possibility of an I^0 or C^0 category to act as the head of categories further down in the same extended projection.[24]

(4.41) *Definition of* ***extended head*** (Bresnan 2001, 132)
Given a c-structure containing nodes $\mathcal{N}, \mathcal{C}$ and c- to f-structure correspondence mapping ϕ, $\mathcal{N}$ is an **extended head** of $\mathcal{C}$ if

[(i)] $\mathcal{N}$ is the minimal node in $\phi^{-1}(\phi(\mathcal{C}))$ that c-commands $\mathcal{C}$ without dominating $\mathcal{C}$ [and

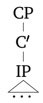
(ii) the X-bar level of $\mathcal{N}$ is less or equal to the X-bar level of $\mathcal{C}$, JK].

For our purposes, it suffices to note that there are two ways of satisfying this condition: either (i) the extended head is just the ordinary X-bar-categorial head; or (ii) if there is no X-bar-categorial head, an X^0 category in the same extended projection (and thus mapping to the same f-structure) becomes the extended head, if it is the lowest one c-commanding the category in question ($\mathcal{C}$). This is illustrated in the following examples.

In (4.42a) and (4.42b), the categories belonging to the extended projection are encircled. In (4.42a), all projected categories have ordinary X-bar-categorial heads: I′ is the head of IP, I the head of I′, etc.[25] In (4.42b) however, the V category is c-structurally unrealized (recall that in the rules all categories are optional). So, V′ has no ordinary head; but the extended head definition applies, making I the extended head of V′: it is mapped to the same f-structure and c-commands V′, without dominating it (and being the only such node, it is also the minimal one).[26]

[24] I made condition (ii) explicit to ensure that IP does not qualify as the extended head of C′ in the following configuration (cf. the discussion of (4.56b) below):

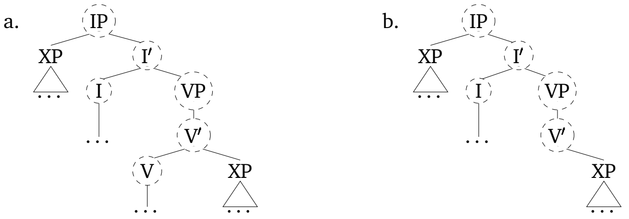
(i)



[25] The X^0 categories themselves do not have extended heads; but note that constraint (4.39b) Ob-Hd does not apply to them.

[26] Note that VP has an ordinary extended head again: V′.

(4.42)



Let us move on to constraints (4.39c) and (4.39d). For Grimshaw's Stay, Bresnan also introduces a purely representational formulation, given in (4.39) as (4.39c) Dom-Hd. I use an additional constraint (4.39d) Arg-as-CF, to differentiate between head mobility (covered by Dom-Hd) and argument mobility (covered by Arg-as-CF). (Note that the formalism would also permit collapsing the two.[27])

A further point to note about (4.39c) Dom-Hd is that there are two ways one may interpret this constraint, depending on how the presuppositional phrase "their extended heads" is resolved. Under the strong interpretation, Dom-Hd is violated even by categories that do not have an extended head at all, so only categories that have an extended head *and* dominate it satisfy the constraint. Under the weaker interpretation, categories without an extended head do not violate Dom-Hd (they *do* violate Ob-Hd of course). As can be seen in the tableau (4.40) on page 80, the interpretation adopted here is the latter one: Candidate b. incurs no violation of Dom-Hd, although the C′ category has no extended head, so it does not dominate one either. A precise formulation of the interpretation adopted would be the following:

(4.43) Dom-Hd (revised formulation)
If a projected category has an extended head, it dominates the extended head.

Pinning down the formulation of constraints with means of a formal language, as will be done in the following, is a guarantee that ambiguities as just observed are excluded.

[27] Bresnan's (2000) system works with just a single Stay constraint: (4.39c). The c-structural introduction of arguments in df positions incurs a violation of this constraint, since the inside-out functional-uncertainty approach is used (cf. the discussion of rule (4.36) above), so there is a phonologically empty argument XP under V′, establishing the token identity of the f-structure under the df and the complement function (typically obj):

(i) [$_{\text{CP}}$ [$_{\text{DP}}$ what] will [$_{\text{IP}}$ she read [$_{\text{DP}}$ ϵ]]]

4.4.2 Universal quantification of constraints

To sum up the observations of the previous subsection, the violable markedness constraints in OT-LFG are formulated as conditions on the structural representations. Both f-structure and c-structure (and the relation between them) are referred to. For formalizing the primitive relations in the f-structural configurations triggering a constraint violation, a description language is already in place: the standard specification language used in LFG's annotations, as introduced in sec. 4.1. As regards c-structure, the configurations referred to in OT constraints may go beyond the local tree accessible within a single context-free rule (the mother and the immediate daughters), but the extension is rather straightforward; it is discussed in sec. 4.4.4.

So, the problem with constraint formalization lies certainly not in the primitive configurational relations. What is more of an issue is the overall logical structure of constraints. The constraints are not formulated with reference to a particular structure, they typically take the shape of universally quantified implications: whenever a structure satisfies the description A, it should also satisfy the description B (or if the constraint is specified negatively, no structure satisfying A should also satisfy B).

A natural reaction is to try and formulate constraints as universally quantified formulae in a feature logic, to range over the complete candidate analysis to be evaluated. This move would make precise the logical structure underlying the natural language formulations of the constraints. I will pursue this idea in the following. Anticipating the result, this approach will turn out unnatural for modelling multiple constraint violations.[28]

Universal quantification

To express universal quantification in the constraints, we need a language that permits universal quantification over the structural objects (f-structures and c-structure nodes), and that contains negation (to express implication). With a feature logic including general negation and universal quantification, we can thus express (4.39a) Op-Spec as (4.44a).

Following B. Keller (1993), one could alternatively use a logic without the universal quantifier, but with general negation and unrestricted functional uncertainty:[29] (4.44b), which is closer to the standard LFG specification language.

[28] This section follows the reasoning in (Kuhn 2001a, sec. 3.2).

[29] Kaplan and Maxwell (1988) assumed a restricted interpretation of functional uncertainty, excluding cyclic interpretation in proving decidability of the satisfaction problem. However, Ron Kaplan (p.c., August 1999) points out that for functional uncertainty outside the scope of negation, the satisfaction problem is generally decidable (correlate of results of Blackburn and Spaan 1993).

(4.44) a. $\forall f.[\exists g.(f \text{ OP}) = g \rightarrow \exists h.(h \text{ DF}) = f]$

b. $\neg[(\uparrow\text{GF*}) = f \wedge (f \text{ OP}) \wedge \neg(\text{DF } f)]$

(4.44b) is expressed here as an f-annotation with ↑ referring to the root node of the grammar, f is a local metavariable for an f-structure, similar to the metavariables ↑ and ↓.

For the constraints on c-structure and the c-structure/f-structure correspondence, the language has to refer to c-structure nodes and tree-geometric relations as well. The options for doing this are discussed in more detail in sec. 4.4.4. For the current purpose, these general considerations may suffice, since the approach will be rejected based on problems with multiple constraint violations.[30]

Constraint marking

With the general form of a constraint being a function from analyses to the natural numbers, we have yet to specify in which way the feature logic formulae are to be applied. Since they are specified in a highly general form, it is conceivable to evaluate them as if attached to the root category of the grammar (for instance, (4.44b) could be technically used in this way). Of course, treating the constraints as ordinary feature logic descriptions to be satisfied by the correct analysis fails to capture violability. Or in other words, the "constraints" would be a part of $Gen_{G_{inviol}}$.

But there is a simple way of allowing candidates to violate the constraint formulae *once* per constraint: The OT constraints are disjoined with their negation, and a constraint violation mark is introduced in case their negation is satisfied. Assume constraint C^1 is specified by the feature logic formula ψ^1, then we can model its application as a violable constraint as

(4.45) $\psi^1 \vee (\neg\psi^1 \wedge \text{`*}C^1\text{'} \in (\uparrow\text{MARKS}))$

attached to the root node. From this MARKS set, the constraint marks can be simply read off: 1 if the constraint mark is in the set; 0 otherwise.[31]

[30] Note that decidability is not an issue with such a logic: Although the general satisfiability problem for feature logics with universal quantification and general negation is undecidable (B. Keller 1993, sec.4.4, Blackburn and Spaan 1993, sec. 5), the use of this logic for constraint checking on given candidate analyses is unproblematic, since the expressions are not used constructively. (This was pointed out by Ron Kaplan (p.c.) and Maarten de Rijke (p.c.).) The task performed is not checking satisfiability, but model checking, which is easy: the given candidate structure has a finite number of nodes and f-structures, thus it can be checked for each of them whether it satisfies the constraints by instantiating the variables to the given elements.

[31] Note that the result will be an LFG grammar that models not only the function $Gen_{G_{inviol}}$ (when used to generate from an input f-structure), but also the function *marks*. We may thus call the grammar $G_{inviol,marks}$. I will briefly come back to this idea in sec. 4.5.

Multiple constraint violations

What happens in a scheme based on the mechanism (4.45) when a candidate analysis contains several instances of the configuration excluded by the constraint? Obviously, the formula ψ^1 cannot be satisfied, so the other disjunct is picked, introducing a single violation mark. Of course, multiple violations of a given constraint up to a fixed upper bound could be simulated by formulating extra constraints that check for the presence of several instances of the violation in the candidate structure.[32] This may be acceptable when the domain of competition is locally confined to non-recursive structures, but it is unnatural for the fully recursive generative system of syntax.

If the possibility of multiple constraint violations is to be granted generally and without an upper bound, the mechanism checking for constraint satisfaction has to be modified. As the candidate structure is traversed, the constraint has to be checked over and over. Whenever the application of a constraint leads to inconsistency, a violation has to be counted, but the rest of the structure has to be checked for further violations of the same constraint.

Since the constraint checking has to traverse the candidate structure anyway, one may ask if there is still the need for formulating the constraint in a universally quantified way. Note that the original idea of this format was to ensure that the constraint ranges over the entire candidate structure (and not just the outermost f-structure, to give a concrete example). Moreover, is it clear at all for arbitrary constraints in such a highly expressive logic what constitutes a multiple violation? For simple implicational constraints with universal quantification over one structural element (an f-structure or a c-structure node) it is intuitively clear what it means to violate this constraint more than once; but it seems that expressions involving more than one universal are more problematic. Assume we wanted to work with the following constraint (4.46a):

(4.46) *Hypothetical constraint*

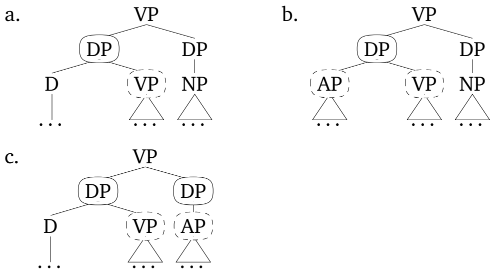
a. For all DP categories, all their daughters are nominal (i.e., either N or D projections).

b. $\forall n.[\text{DP}(n) \rightarrow \forall m.[dtr(m,n) \rightarrow nom(m)]]$

Now, the following structures are evaluated:

[32] Karttunen (1998) proposes this for his computational model of OT phonology, which does not allow arbitrarily many violations of a constraint either. (But see Gerdemann and van Noord 2000.)

(4.47)



None of the three satisfies (4.46). But how many violations does each of them incur? In (4.47a) and (4.47b), one DP fails to satisfy the condition that all its daughters are nominal, while in (4.47c), both do. So, under one interpretation, (4.47a) and (4.47b) should violate (4.46) once, and (4.47c) twice.

On the other hand, (4.47a) is better than (4.47b), because only one of the DP's daughters violates the inner implication. Shouldn't one expect then that (4.47b) incurs two violations? In fact, the modified checking mechanism sketched above, which counts sources of inconsistency, would presumably have this effect (unless the mechanism is explicitly set back to the outermost universal whenever an inconsistency is encountered).

The problem is also clearly brought out if we look at the following two reformulations of (4.46):

(4.48) a. Each daughter of a DP category is nominal.

b. $\forall m.[\exists n.[dtr(m,n) \wedge \mathrm{DP}(n)] \rightarrow nom(m)]$

(4.49) a. For every category, if it has a non-nominal daughter, then it is not a DP.

b. $\forall n.[\exists m.[dtr(m,n)\ \wedge\ \neg nom(m)] \rightarrow \neg\mathrm{DP}(n)]$

Both are equivalent to (4.46) in terms of classical predicate logic, but read with the intuitions behind violable constraints, they clearly differ in the number of violations ascribed to (4.47b): (4.47b) violates (4.48) twice, but it violates (4.49) only once. This indicates that the use of general formulae of this type of feature logic is inappropriate for modelling the intuitions behind OT constraints, for which we need a precise way of stating what it means to incur multiple violations of a given constraint.

4.4.3 Constraint schemata

The recursive applicability of constraints over the entire candidate structures has to be inherent to the general constraint marking mechanism in order to allow arbitrary multiple violations. Hence, the universal range does not have to be stated explicitly in each individual constraint. To the contrary, this makes the constraints counterintuitive, as was discussed in the previous section.

Thus, we should give the individual constraint formulations a simpler logical structure – this is also in line with the methodological principles discussed particularly in sec. 2.2.4 (cf. also Grimshaw 1998). Now, the universal applicability is implicit to all constraints and will be made effective in the checking routine that the candidate structures have to undergo after they have been constructed. At every structural object (either a c-structure node *or* an f-structure), all constraints are applied. This application of the constraints to multiple objects is the only source for multiple violations – a single structural element can violate each constraint only once. At each application, the individual constraints are again interpreted classically.

In order for this to work, the structural object which is being checked with a given constraint has to be clearly identified. I will assume a metavariable $\star$ for this (reminiscent of the $*$ used in standard LFG f-annotations of categories to refer to the category itself, cf. page 56). (4.48) will for example take the following shape:

(4.50) $\exists n.[dtr(\star,n) \wedge \mathrm{DP}(n)] \rightarrow nom(\star)$

When the constraints are checked, the metavariable $\star$ will be instantiated to one structural element after the other. Thus, the constraints are actually specified as constraint schemata, generating classical constraints.

Note that we could now express (4.46b) in either of the following two ways, reaching the two different effects for the structures in (4.47) discussed above:

(4.51) a. $\mathrm{DP}(\star) \rightarrow \forall m.[dtr(m,\star) \rightarrow nom(m)]$

b. $\forall n.[\mathrm{DP}(n) \rightarrow (dtr(\star,n) \rightarrow nom(\star))]$

Expressing (4.51b) in the equivalent form (4.50) may actually be more intuitive (note that now, equivalences of classical logic apply again).

So, we can state the following restriction on constraint formulation, which allows for a simple concept of multiple violations that is compatible with a classical concept of satisfiability, and also meets the intuitions behind violable constraints in OT:

(4.52) *Restriction on the form of constraints*
Violable constraints are formulated with reference to a unique structural element, which is referred to by a metavariable ($\star$).

Scalar constraints

Note that it is compatible with this restriction to assume a "scalar" interpretation of alignment constraints like, e.g., Head Left (4.53) from (Grimshaw 1997).[33] (Under a scalar interpretation, this constraint is violated twice if there are two intervening elements between a (single) head and the left periphery of its projection.)

(4.53) Head Left: (Grimshaw 1997, 374)
The head is leftmost in its projection.

The metavariable-based formulation allows a clear distinction between the non-scalar and the scalar version of this constraint (it is assumed that the function *proj* and the relations *dtr* and *precede* are defined appropriately):

(4.54) Head Left

non-scalar interpretation

$$\mathit{head}(\star) \rightarrow \neg\exists n.[\mathit{dtr}(n, \mathit{proj}(\star)) \wedge \mathit{precede}(n, \star)]$$

scalar interpretation

$$\mathit{cat}(\star) \rightarrow \neg\exists n.[\mathit{head}(n) \wedge \mathit{dtr}(\star, \mathit{proj}(n)) \wedge \mathit{precede}(\star, n)]$$

The first formulation is stated from the point of view of the head; since the instantiated schema is interpreted classically (i.e., incurring maximally one constraint violation for each structural element), a given head can violate this constraint only once (even if there are several intervening nodes to the left of it). The second formulation is from the point of view of the intervening category; thus if there are several of them, the overall structure will incur several violations of this constraint.

[33] In recent work, Sells (e.g., (1999, 2001)) has proposed an antisymmetric constraint system for deriving the typologically attested space of c-structure configurations, using alignment constraints of this kind.

Formalization of the example constraints

With the formal means of constraint schemata, we are in a position to give the example constraints from (4.39) a precise formulation. English paraphrases for the formal specifications are given below the formulae.

(4.55) a. Op-Spec (Bresnan 2000)
An operator must be the value of a DF in the f-structure.

$$\begin{aligned}(\mathit{f\text{-}str}(\star) \wedge \exists v.[(\star\ \textsc{op}) = v])\\ \rightarrow \exists f.[(f\ \textsc{df}) = \star]\end{aligned}$$

"If $\star$ is an f-structure bearing a feature OP (with some value), then there is some (other) f-structure f such that $\star$ is embedded in f under the feature DF."

b. Ob-Hd (Bresnan 2000, (21))
Every projected category has a lexically filled [extended, JK] head.

$$(\mathit{Xbar\text{-}cat}(\star) \vee \mathit{Xmax\text{-}cat}(\star)) \rightarrow \exists n.[\mathit{ext\text{-}hd}(n, \star)]$$

"If $\star$ is an X-bar or X-max category, then there is some node n which is the extended head of $\star$."

c. Dom-Hd (revised formulation)[34]
If a projected category has an extended head, it dominates the extended head.

$$\forall n.[(\mathit{cat}(\star) \wedge \mathit{ext\text{-}hd}(n, \star)) \rightarrow \mathit{dom}(\star, n)]$$

"For all nodes n such that category $\star$ is their extended head, n dominates $\star$."

d. Arg-as-CF
Arguments are in c-structure positions mapping to complement functions in f-structure.

$$\exists f.[(f\ \textsc{cf}) = \star] \rightarrow \exists n.[\mathit{cat}(n) \wedge \phi(n) = \star \wedge \mathit{lex\text{-}cat}(\mathcal{M}(n))]$$

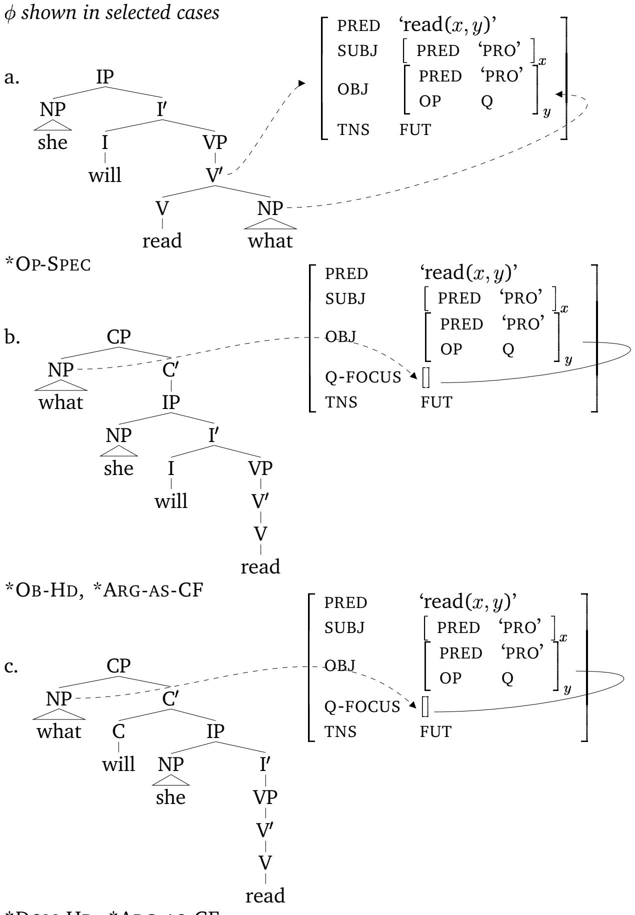
"If $\star$ is embedded under a complement function CF (in some f-structure f), then there exists a category node n projecting to $\star$, whose mother is a lexical category, i.e., $\star$ is c-structurally introduced as the complement of a lexical category (the canonical position for CF introduction, according to the mapping principles, Bresnan 2001, sec. 6.2)."

[34] Note that the alternative, stronger interpretation of Stay discussed in connection with (4.43) can be easily expressed too:

$$(\mathit{cat}(\star) \rightarrow (\exists n.[\mathit{ext\text{-}hd}(n, \star) \wedge \mathit{dom}(\star, n)]))$$

When these constraints are applied to the sample candidate set of (4.37) on page 77, we get the following constraint violations listed under the analyses:

(4.56) *Candidate analyses for tableau (4.40), with the correspondence mapping ϕ shown in selected cases*



a. *Op-Spec

b. *Ob-Hd, *Arg-as-CF

c. *Dom-Hd, *Arg-as-CF

The constraint violations are derived as follows: In candidate (4.56a), we have an f-structure that satisfies the antecedent of the implication (4.55a), the Op-Spec constraint: the f-structure under obj bears the feature op q. Let us call this f-structure ⋆ for the moment. To satisfy Op-Spec, ⋆ has to be embedded in some f-structure under a feature df. This is not the case in candidate (4.56a), thus we get a violation *Op-Spec. Note that both of the two other candidates satisfy Op-Spec, since there the obj is token-identical with the value of q-focus (an instance of df).

The f-structure ⋆ we were looking at in candidate (4.56a) *does* however satisfy the remaining three constraints: Constraints (4.55b) and (4.55c) are satisfied trivially, since our ⋆ is not a c-structure category so the antecedent is already false (making the implication true). However let us look at constraint (4.55d) Arg-as-CF: with f instantiated to the outermost f-structure (the only possibility), the antecedent is satisfied: ⋆ is indeed embedded under a cf, namely obj. So does ⋆ also meet the consequent? There is only one category projecting to ⋆: the lower NP node, and fortunately its mother – V′ – is a lexical category, as required. So we get no violation of Arg-as-CF. All other c-structure and f-structure elements of candidate (4.56a) satisfy all four constraints, so *Op-Spec is the only constraints violation we get.

Let us now look at candidate (4.56b). Since there is no C category in the tree and IP does not qualify as the extended head of C′ (cf. definition (4.41) and footnote 24 on page 81), we get a violation of (4.55b) Ob-Hd. Checking (4.55d) Arg-as-CF, we can again instantiate f as the outermost f-structure, and ⋆ as the f-structure under obj. There is a single category node mapping to ⋆: the NP in the specifier to CP (note that the f-structure under obj and q-focus is token-identical). In order to satisfy the constraint, the mother node of this NP – CP – would have to be a lexical category. This is not the case, so we get *Arg-as-CF. The other constraints are fully satisfied.

Candidate (4.56c) shares with (4.56b) the configuration violating Arg-as-CF. If we look at C′ however, we note that (4.55b) Ob-Hd is satisfied here: since C is filled we do find an extended head. Note that I′ too has an extended head, although there is no X-bar-categorial head I; C is in the appropriate c-commanding position and has the right bar-level. However, I′ violates (4.55c) Dom-Hd: since it has an extended head, it would also have to dominate this head for satisfying Dom-Hd.

With the constraint ranking Op-Spec, Ob-Hd ≫ Arg-as-CF, Dom-Hd for English, we get (4.56c) as the most harmonic of these three (and in fact all possible) candidates, as shown in tableau (4.40) already.

Constraint marking

Based on the constraint schemata proposed in this section, the marking of constraint violations incurred by a given candidate structure is conceptually straightforward. For each structural element (c-structure node and f-structure), the set of constraints is applied, with the metavariable instantiated to the respective element. When the application of a constraint fails, the candidate is not rejected, but the count of constraint violations is increased.

So, the constraint marking function from candidate analyses to natural numbers can be given a precise specification, based on the cardinality of the set of structural elements for which the instantiated constraint schema is not satisfied by the candidate analysis:[35]

(4.57) *Schema-based definition of an OT constraint*

$$C^i(\langle T, \Phi\rangle) = \ |\{x \mid \ x \text{ is a structural element of } T, \Phi \text{ and } \langle T, \Phi\rangle \not\models \psi^i[\star/x] \}|,$$

where $\psi^i[\star/x]$ is a constraint schema ψ^i formalizing C^i, with x instantiating the metavariable $\star$.

4.4.4 Constraint schemata as standard LFG descriptions

In this section, I adjust the formulation of OT constraints further, based on the observation that it can be brought closer to the formulation of familiar, classical constraints in the LFG framework. The expressiveness is slightly reduced by this move, which should be considered an improvement, since the linguistically relevant constraints for OT syntax can still be expressed.

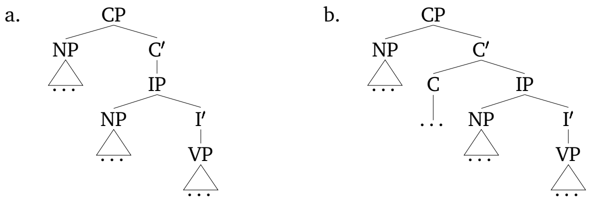
OT constraints of c-structure

The constraint formalization of the previous section (and Kuhn 2001a) makes use of intuitively named predicates over categories and tree configurations (e.g., *ext-hd*, *dom*, *lex-cat*, etc.). A precise definition for these predicates was not given since the focus of presentation was on the question how to formalize the idea of multiply violable constraints. Nevertheless we need to find a more explicit account.

[35] The adoption of a set-theoretical view was suggested by Ron Kaplan (p.c.) and Dick Crouch (p.c.).

A slight difficulty in this task is that the intuitive difference between classical LFG constraints and typical OT constraints seems larger for constraints on c-structure than for constraints on f-structure. In the latter case, propositions about certain graph configurations have classically been expressed as Boolean combinations of various types of equations. This can easily be transferred to violable OT constraints, which add certain implications etc. For constraints on c-structure, the classical means of expression in LFG have been context-free rewrite rules (extended to allow regular operations such as optionality, union/disjunction, and Kleene closure). Here, it is not so obvious how the typical implications of OT constraints should be added. For instance, at what level should the difference between the I′ nodes in the following tree structures (one satisfying, one violating OB-HD) be stated?

(4.58)



There are various possible formats for stating such c-structure constraints. Underlying in the previous section there was a tendency to move away from the standard means of grammar specification in LFG, suggesting the introduction of a totally new tree specification language. So, on the one hand the trees in (4.58) are constructed according to the inviolable constraints in *Gen*$_{G_{inviol}}$, which are formulated in the form of (extended) context-free rewrite rules. But for the violable OT constraints, a new, more general tree description language has been assumed.

For an analysis of further computational properties of the account, this move is problematic, since it would make the transfer of formal results from classical LFG to our situation unnecessarily difficult. It is also possible to state the constraints in a more familiar format.

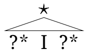
We have still at least two choices: one could follow the proposal of Andrews and Manning (1999), who modify the classical projection architecture of LFG to encode categorial structure as attribute-value matrices (inspired by HPSG[36]). In such a framework, implicational OT constraints could be expressed as combinations of feature equations describing these attribute-value matrices.

[36] Head-Driven Phrase Structure Grammar, Pollard and Sag 1994

The other alternative, which I will follow here, does not involve any modification of the classical f-structure representation of LFG. The additional constraints on c-structure are expressed as regular expressions over sequences of categories in local subtree configurations.[37] For instance, a constraint could demand that in a local subtree dominated by I′, an I daughter is present: (4.59).[38] The general format of constraints is implicational $A \Rightarrow B$, to be read as "if a local configuration satisfies description A, then it also has to satisfy description B in order to satsify the constraint".

(4.59) *Illustrative constraint:* I′-HAS-I-HEAD

$\star$=I′ $\Rightarrow$



With just the ordinary set of c-structure symbols available, this account has a very limited expressiveness. The different status of (4.58a) and (4.58b) could not be detected, since at the local subtree level, the two representations are indistinguishable.

However, we can extend the set of category symbols to allow for more fine-grained distinctions to be made. The standard convention is to encode the lexical class (N, V, A, P), the bar level and the functional/lexical distinction in the category symbols. Some of this information would be recoverable from the tree structure; for example, if the lexical class was only encoded in the X^0 categories and not in their projections, one could still detect it by tracing down the X-bar projection line.[39] With the explicit encoding of lexical class in higher projections, this information is made available up to the XP level, where it is required to express constraints on possible combinations of maximal categories with other material. So, the definition of the X-bar categorical head is effectively precomputed: the rewrite rules are specified in a way that ensures that the lexical class of a projection is the same as the one of its projecting X^0 head.

Now, the same idea of precomputing relevant information from the c-structure configuration and providing it as part of a category name can be applied in other situations. For instance we could distinguish between IPccxhy and IPccxhn (for *c-commanding extended head yes/no*), based on rules like the following:

[37] I use the term local subtree to refer to subgraphs of trees with depth 1.

[38] As in the XLE system's rule notation, the '?' is assumed to denote arbitrary category symbols; the stars ('*') are Kleene stars. So, the regular expression on the lower side of the local tree in (4.59) is matched by all category strings containing at least one occurrence of I.

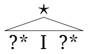
[39] This reasoning is based on a more classical set-up, where the X^0 heads cannot be missing; to extend it to the current LFG set-up where all categories including heads are optional, one might assume that projections with missing X^0 heads are underspecified for lexical class.

(4.60)
$$\begin{array}{rcll}
\text{C}' & \rightarrow & \text{C} & \text{IPccxhy} \\
\text{C}' & \rightarrow & & \text{IPccxhn} \\
\text{IPccxhy} & \rightarrow & \text{(XP)} & \text{I}'\text{ccxhy} \\
\text{IPccxhn} & \rightarrow & \text{(XP)} & \text{I}'\text{ccxhn} \\
\text{I}'\text{ccxhn} & \rightarrow & \text{(I)} & \text{(VP)} \\
\text{I}'\text{ccxhy} & \rightarrow & \text{(I)} & \text{(VP)}
\end{array}$$

The symbol IPccxhn is introduced in the second of the two C′ productions, i.e., when a c-commanding extended head (i.e., the C category) is missing: this information is propagated down to the I′ level. (Of course, the same construction would have to be introduced for the VP, but this is omitted here for simplicity.) We can now formulate the exact conditions for the OB-HD constraint at this level:

(4.61) *Partial specification of constraint:* OB-HD

$\star$=I′ccxhn $\Rightarrow$



Without the c-commanding extended head being present, the I′ has to have a local I head in order to satisfy OB-HD; when a c-commanding extended head is present, there are no restrictions on the local subtree.

With the described technique of threading the relevant information through the c-structure skeleton, all distinctions with a finite set of relevant choices can be "imported" to the scope of a local subtree.

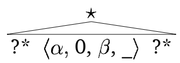
Explicit generalizations over c-structure

A possible objection to the proposed scheme of formulating c-structural constraints is that generalizations are not expressed explicitly in the $Gen_{G_{inviol}}$ rules and in the OT constraints. Instead, a massively disjunctive specification seems to be required for non-trivial systems.

However, there are several ways of ensuring that at the level of grammar specification, the underlying generalizations are indeed explicit. In (Kuhn 1999b, 4.1), I distinguish two strategies: the representation-based vs. the description-based formulation of c-structural generalizations. In both cases, the idea is that entire classes of categories can be constrained with a single rule or principle. The representation-based strategy modifies the representation of categories, no longer viewing them as atomic symbols but assuming an internal structure (thereby making explicit a conceptual classification that is assumed anyway). The IP category, for instance, can be seen as a combination of category-level "features" for lexical class V, bar-level 2 (or *maximal*), and category type *functional*, which we may write as ⟨V, 2, *func*⟩. It is obvious how further distinctions can be added to this scheme (to give us ⟨V, 2, *func*, ccxhy⟩, for instance, to signal the existence of a c-commanding extended head). As long as all features have a finite range of values and there is a finite number of features, the fundamental LFG set-up remains unchanged.[40] But now, generalizations over rules can be expressed more explicitly by constraining the co-occurrence of category features within rules. In particular, OT constraints can be formulated that express implications based on particular category features, leaving the rest underspecified. A more general specification of (4.61) would be

(4.62) *Generalized (partial) specification of constraint:* OB-HD

$\star$=$\langle\alpha$, 1 $\vee$ 2, β, ccxhn$\rangle$ $\Rightarrow$



Note that as a prerequisite for this technique of constraint specification, principles about the inheritance of all relevant category-level features in the G_{inviol} have to be explicitly stated. It is beyond the scope of the present discussion to go into details of such a specification. I will assume that G_{inviol} is specified in such a way that (i) the c-structure in all candidate analyses is in accordance with the intuitive definition of the properties encoded by the category-level features, and (ii) all combinations of categories conforming with the definitions are effectively generated. The G_{inviol} grammar specification is simply taken as the formal definition of all category-level features involved, so there is no danger of generating any incorrect candidates (in a technical sense).

The other strategy for expressing generalizations about c-structure (the description-based formulation) keeps up atomic category symbols, but provides a richer language for describing categories: the category IP is in the denotation of meta-category names like *V-cat*, *Xmax-cat*, and *Func-cat*, which can be intersected as appropriate. This strategy can be directly integrated into the classical regular-language specification of LFG rules. However, it does not allow one to generalize over entire classes of meta-categories, so I keep to the representation-based strategy assuming complex categories.

Excluding universal quantification from the constraint schemata

Having simplified the formulation of c-structural OT constraints, we should now take another look at universal quantification (which is not included in

[40] The XLE implementation provides the discussed concept of complex categories, constraints about which are formulated in *parametrized rules*. For the category-level features a positional encoding is used; the format for complex categories is `XP[a,b]`.

the means of expression of standard LFG). According to sec. 4.4.3 (and Kuhn 2001a) universal quantification is still allowed in the constraint schemata, although it is no longer used to account for multiple constraint violations (cf. the discussion of sec. 4.4.2). In the formulation of sample constraints in sec. 4.4.3, we do find a use of the universal quantifier, in the DOM-HD constraint (4.55c), repeated below.

(4.55) c. DOM-HD (revised formulation)

If a projected category has an extended head, it dominates the extended head.

$$\forall n.[(cat(\star) \wedge ext\text{-}hd(n,\star)) \rightarrow dom(\star, n)]$$

"For all nodes n such that category $\star$ is their extended head, n dominates $\star$."

Clearly, this universal quantification has been made obsolete by the move to the more canonical formulation of c-structural OT constraints, according to which the property of having an extended head is now encoded in the c-structure categories. But even without this move, the use in (4.55c) would not justify the need for full universal quantification: according to the definition of extended head (see (4.41), adapted from Bresnan 2001, 132, and note the minimality condition), the relation *ext-hd*(A, B) could be rewritten in a functional notation, with *ext-hd*$'(B) = A$. So, (4.55c) could be reformulated as follows:[41]

(4.63) $cat(\star) \rightarrow dom(\star, ext\text{-}hd'(\star))$

Further uses of universal quantification occur in the two versions of the hypothetical constraint first introduced in (4.46) and discussed in sec. 4.4.3. Their schema-based specification is repeated below.

(4.51) a. $\text{DP}(\star) \rightarrow \forall m.[dtr(m,\star) \rightarrow nom(m)]$
b. $\forall n.[\text{DP}(n) \rightarrow (dtr(\star, n) \rightarrow nom(\star))]$

Concerning (4.51b), we can again exploit the functional character of the daughter relation: $dtr(A, B)$ iff $\mathcal{M}(A) = B$, which gives us

[41] *ext-hd*$'$ is a partial function – some categories have no extended heads. One might define a proposition containing an undefined functional expression to be false, then the consequent of (4.63) would become false, and the entire constraint would become true/satisfied for a category which has no extended head.

(4.64) $\mathrm{DP}(\mathcal{M}(\star)) \rightarrow \mathit{nom}(\star)$

In (4.51a), we do have a "real" example of universal quantification. The intuition is that in order to satisfy this constraint, *all* daughters of category $\star$ have to be nominal. But since the property checked for in the constraint – having nominal daughters exclusively – is locally confined, it would be possible to introduce a complex-category-level distinction on mother categories encoding whether or not they have this property. Then the constraint would only need to check for the relevant category feature. Alternatively, a binary-branching re-coding of the c-structure could be assumed and the property *nom* could be checked with a simple constraint schema at each level, so the universal-quantification effect would be shifted to the universal application of constraint schemata.

I take these examples to show that after the move to constraint schemata, which are evaluated at every structural object, universal quantification is no longer required for linguistically interesting constraints. In fact it goes against the general principle of keeping the individual constraints simple and exploiting constraint *interaction* for higher-level effects.

This means in particular that for the f-structural OT constraints we can restrict the format available for the formulation of constraint schemata to the format of standard LFG f-annotations (with the metavariable $\star$ added). Note that this excludes constraints like the following, universally quantifying over all possible feature paths in an f-structure:

(4.65) $\forall \textsc{path}, f.[(\star\ \textsc{path}) = f \rightarrow (f\,\textsc{check}) = +]$

This constraint checks an entire f-structure with all substructures for a particular property ([CHECK +]). Note that when this schema is instantiated with different partial f-structures, we get a funny behaviour: a violation originating from a certain embedded f-structure g lacking the specification [CHECK +] is counted over and over again; so, we get multiple violations of the constraint, but the number of violations does not depend on the number of offensive partial f-structures, but rather on the size of the overall f-structure. A more reasonable behaviour results if we use the metavariable for the local f-structure that is demanded to have the specification [CHECK +]. In other words, we do away with universal quantification within the constraint schemata.

So, concluding this section, the constraints in the OT-LFG setting can be restricted to (i) conditions on local subtrees in c-structure (making use of complex category specification for generality), and (ii) functional annotations containing the metavariable $\star$. In addition, we allow for a combination of c-structural and f-structural restrictions, so OT constraints can express conditions on the structure-function mapping. This restricted format will be most relevant for decidability considerations discussed in sec. 6.2. For other discussions in the following, I will keep up the more perspicuous constraint schema format using intuitive predicates and universal quantification.

4.5 Constraint marking: description by analysis vs. codescription

Given the schema-based definition of constraints, the overall constraint violation profile of a given candidate results when the counts for the individual constraints are taken together. The way candidate set generation and constraint marking have been defined suggests a clear conceptual split between the two abstract processes: Candidate generation is prior to constraint marking, and one may want to think of the latter starting only once the former has finished. However, with the restriction to constraint schemata referring to single structural elements, an alternative way of conceiving of constraint marking is opened up: we may envisage candidate generation and constraint marking as a combined abstract process. This alternative view has certain advantages, for instance in practical grammar writing, where the constraint marking can be coded into the grammar rules specifying the inviolable principles. In this section, I will make a few remarks about the two views.

There is a parallel to different approaches of realizing semantic construction in an LFG grammar: the *description by analysis* approach vs. the *codescription* approach. In the former, semantic construction starts only once the f-structure analysis has been created; in the latter, f-structure and semantic structure are built up simultaneously (see e.g. Kaplan 1995 for discussion). The constraint marking approach working with two separate abstract processes works as description by analysis. The constraint violation profile of a candidate (corresponding to semantic structure) is built by traversing the previously constructed syntactic analysis.

But as long as there is a unique place in the grammar/lexicon from which a certain structural element can be introduced, we can attach the constraints it has to meet in the rule or lexicon entry already. This becomes possible since the constraints are formally restricted to be talking about a single structural element. What we have got now is a codescription approach. For c-structure categories, it is true that there is such a unique place: we can attach the constraints in the rules for nonterminals and in the lexicon entries for terminals. With f-structures, we have to be careful, since due to unification, there is not generally a unique source in the grammar/lexicon for an f-structure. For all PRED-bearing f-structures, the instantiated symbol interpretation of semantic forms (cf. page 59) guarantees uniqueness however. Hence, attaching the constraints wherever a PRED-value is introduced captures this subset of f-structures, and a generalization to all f-structures is possible.[42] This means that a general conversion from description by analysis to codescription – and vice versa – is possible.

As in the grammar-based constraint marking discussed briefly in sec. 4.4.2 (cf. footnote 31 on page 85), we have to ensure the violability of the attached OT constraints. We can again disjoin the constraints with their negation – this time not just for the root category, but potentially for every category in each rule. As a result we will again have a grammar that performs both the task of candidate generation and constraint marking; thus we might call it $G_{inviol,marks}$.

Constraint violation marks are introduced to the MARKS multiset in the places in the grammar where the structure violating a constraint is created. For example, we may want to formulate the constraint (4.55c) DOM-HD by making the following annotation in each of the grammar rules (cf. (4.34)):

$$\text{(4.66)}\quad \mathrm{C}' \longrightarrow \left\{ \begin{array}{c} \mathrm{C} \\ \uparrow = \downarrow \end{array} \middle| \begin{array}{c} \epsilon \\ {*}\textsc{Dom-Hd} \in (\uparrow \textsc{marks}) \end{array} \right\} \text{(IP)}$$

In the original rule, the head C was simply optional "(C)", now we have an explicit disjunction of C and the empty string ϵ. At c-structure, this is equivalent (ϵ is not a phonologically empty category, it is indeed the empty string in the formal language sense). However, at f-structure, we can now annotate the option not realizing C with the introduction of the constraint violation mark *DOM-HD.

Since constraint marks can now be introduced into the MARKS multiset in every rule, we have to ensure that all contributions are collected and made available at the root node of the analysis.[43] This can be achieved by identifying the MARKS feature of all daughter constituents with the mother's by the equation (↑MARKS) = (↓MARKS), creating a single multiset for the complete analysis. Note that multiple violations of a single constraint fall out from the use of a multiset.[44]

[42] The generalization would work as follows: even for f-structures without a PRED-value, a feature taking an instantiated symbol as its value is assumed. Let us call it ID. The Completeness condition is extended to demand that in a well-formed f-structure, all substructures contain this feature ID. The value for ID is introduced in the constraint marking schemata for f-structures, which are *optionally* applied in all rules and all lexicon entries, whenever there is a reference to an f-structure. Since the value is an instantiated symbol, only one application of the schemata can be performed on each f-structure. When there is unification, i.e., other rules or lexicon entries referring to the same f-structure, the optionality of application will ensure that they are not applied again. But Completeness ensures that they are applied once. Of course there is a non-determinism leaving open which rule/lexicon entry is the one setting the ID value. But this does not affect the result.

[43] As Ron Kaplan (p.c.) pointed out, the collection of marks need not be realized within the grammar of course, since evaluation is a grammar-external process anyway; thus, the identification of the MARKS feature is an unnecessary overhead.

If we now use a special projection o instead of the feature MARKS (so the membership constraint from (4.66) reads as "*DOM-HD $\in o$") we are very close the system of (Frank, King, Kuhn, and Maxwell 2001), which is built into the Xerox Linguistic Environment (XLE) LFG parsing/generation system. The projection o is always a multiset of constraint violation marks and we can assume implicit trivial equations in the rules, so the o-structure of all constituents is identified. The XLE system also provides an (extended) implementation of the *Eval*-function, based on the marks introduced to the o-projection, and a dominance hierarchy specified in the configuration section of the grammar.[45]

One advantage of the grammar-based or codescription approach is that often the constraint formulation becomes simpler: the triggering configurations for constraint satisfaction/violation do not have to be restated when they have an obvious location in the grammar specification. A good example is constraint (4.55d) ARG-AS-CF: the description-by-analysis approach with the strict separation of candidate generation and constraint marking enforces a remodelling of the c-structure configuration in which complements of lexical categories are mapped to the embedded CF. In the codescription account, a constraint violation mark can be introduced when an argument is c-structurally introduced in the non-canonical position, making use of functional uncertainty.[46]

[44] An alternative way using a standard set would be to interpret the constraint marks introduced as instantiated symbols (like the PRED values in standard LFG), i.e., as pairwise distinct.

[45] As Frank, King, Kuhn, and Maxwell (2001) discuss in detail, XLE distinguishes several types of constraint marks – in particular preference marks besides dispreference marks. For the purposes of modelling a standard OT account, the dispreference marks suffice.

[46] The two formulations are not strictly equivalent. When an argument is realized in the two c-structural positions simultaneously (like split NPs in German, according to the analysis of Kuhn 1999a; Kuhn 2001c), the description-by-analysis formulation is satisfied, whereas the codescription formulation is violated. It depends on the linguistic account which variant meets the intentions.

(4.67) ARG-AS-CF
Arguments are in c-structure positions mapping to complement functions in f-structure.

Description-by-analysis formulation

$$\exists f.[(f\ \textsc{cf}) = \star] \rightarrow \exists n.[\mathit{cat}(n) \wedge \phi(n) = \star \wedge \mathit{lex\text{-}cat}(\mathcal{M}(n))]$$

Codescription formulation (just adding the violation mark introduction to rule (4.36))

$$\begin{array}{lccc} \text{CP} & \longrightarrow & (\text{XP}) & (\text{C}') \\ & & (\uparrow \textsc{df}) = \downarrow & \uparrow = \downarrow \\ & & (\uparrow \textsc{df}) = (\uparrow \{\textsc{comp} \mid \textsc{xcomp}\}^{*}\ (\textsc{gf}\text{–}\textsc{comp})) & \\ & & {}^{*}\textsc{Arg-as-CF} \in o & \end{array}$$

A further, practical advantage of the grammar-based constraint marking is that it makes it easy to focus on some specific phenomenon, abstracting away from irrelevant interactions. This allows a linguist to write an experimental grammar fragment rather fast: writing the LFG grammar that models $Gen_{G_{inviol}}$ happens simultaneously to thinking about the constraints. So, in particular one can focus attention on a small set of relevant constraints, only generating the candidate distinctions at stake.[47] Different hypothesis can be checked very quickly. Parts of the grammar that are not at the center of attention can be realized with a classical LFG analysis.

Of course, the fact that the grammar writer herself/himself can decide which constraints to check in which rule bears a certain risk, especially when the fragment grows over time: important interactions may be misjudged as irrelevant and thus left out. Later decisions are then set against an incorrectly biased background, and it may get hard to keep the entire constraint system under control. This is a familiar risk in grammar writing, occurring whenever some underlying generalizations are not made explicit in the grammar code.[48] So the selective strategy of constraint checking is presumably best applied to small or medium-sized grammar fragments of theoretical interest. For larger fragments, the learnability of OT systems based on empirical data should be exploited and thus the space of candidate variance should not be restricted too much by manual preselection.

[47] With this strategy, it was relatively easy to implement the relevant aspects of the OT fragment of (Bresnan 2000, sec. 2) in the XLE system, i.e., leaving aside instances of constraint violation where they were obviously irrelevant.

[48] See (Kuhn and Rohrer 1997; Kuhn 1998; Kuhn 1999b; Butt, Dipper, Frank, and King 1999; Butt, King, Niño, and Segond 1999; King, Dipper, Frank, Kuhn, and Maxwell 2000) for relevant discussion.

4.6 Faithfulness constraints

In sec. 4.4, OT constraints were discussed, with a limitation to those constraints that can be checked on the candidate analysis alone (i.e., without reference to the input). This seems to exclude faithfulness constraints, which are violated exactly in those cases where the candidate analysis diverges from the input. Furthermore, the restriction of the candidate generation function $Gen_{G_{inviol}}$ made in sec. 4.3 (definition (4.30) is repeated below for convenience) seems to preclude (overly) unfaithful candidates from getting into the candidate set in the first place: by definition, all candidates are f-structurally subsumed by the input f-structure and may not add any semantically relevant information.

(4.30) *Restricted definition of **Gen***

$$Gen_{G_{inviol}}(\Phi_{in}) = \{ \langle T, \Phi' \rangle \in L(G_{inviol}) \mid \Phi_{in} \sqsubseteq \Phi', \text{ where } \Phi' \text{ contains no more semantic information than } \Phi_{in} \}$$

Excluding unfaithful candidate in $Gen_{G_{inviol}}$ – even if it was just for the massively unfaithful candidates – would go against the methodological principle (3.1), according to which as much as possible should be explained as a consequence of constraint interaction. The fact that overly unfaithful candidates play no role when it comes to finding the most harmonic candidate should follow from constraint interaction alone. So, $Gen_{G_{inviol}}$ should provide arbitrarily serious faithfulness violations. As discussed in sec. 3.2.4, the candidate set for *Ann laughed* should for example contain the following candidate strings (and infinitely many more):

(3.19) a. Ann laughed
b. Ann did laugh
c. it laughed Ann
d. laughed
e. Ann
f.
g. she laughed
h. she did
i. Ann yawned
j. John yawned
k. Ann saw him, etc.

As I will show in this section, the restriction of $Gen_{G_{inviol}}$ *is* indeed compatible with the intuitive concept of unfaithfulness in syntax, as discussed in sec. 3.2.3. Morevover, this restriction makes redundant a dependence of faithfulness constraints on the input (besides the candidate analysis), so the form of constraints introduced in sec. 4.4 encompasses both markedness constraints and what is intuitively regarded as faithfulness constraints.

The last point involves a terminological issue, which I would like to clear up in advance: it is conceivable to *define* faithfulness constraints as opposed to markedness constraints by their reference to the input. Under this terminology the point of this section is to show that the representations assumed in syntax work best with a system employing no faithfulness constraints at all. However, I will keep up the intuitive terminology where a faithfulness violation occurs when the surface form diverges from the underlying form, not implying that the constraints do really access the input representation.

4.6.1 Faithfulness and the subsumption-based conception of $\boldsymbol{Gen_{G_{inviol}}}$

Definition (4.30) looks very restrictive, with the subsumption condition disallowing the deletion of input information (as seems to be required for modelling MAX-IO violations, cf. (3.14), repeated here), and an additional clause excluding the addition of semantic information (cf. DEP-IO violations/epenthesis, cf. (3.7)).

(3.14) *Dropped pronominal in Italian*

a. He has sung

b. _ ha cantato
has sung

(3.7) *Expletive do in English*

a. Who did John see

b. Wen sah John
whom saw John

However, the restrictive definition of $Gen_{G_{inviol}}$ has at least two motivations: learnability (discussed in sec. 3.3) and computational complexity (which will be discussed further in chapter 6). Hence, it would be problematic to relax the restriction in order to permit the generation of unfaithful candidates. But the intended faithfulness violations *can* indeed be captured within the limits of this definition, by regarding unfaithfulness as a tension between f-structure and the categorial/lexical realization: At f-structure, semantic information may neither be added nor removed (thus the interpretation of all candidates is identical, which is important for the learner to rely on). C-structure on the other hand may contain material without an f-structure reflex (epenthesis), or leave f-structure information categorially unrealized (deletion). In the setup of LFG, this possibility can be conveniently located in the (morpho-)lexical annotations.

The lexical f-annotations specify semantic and morphosyntactic information. (4.68) shows the lexicon entry for (the full verb) *did* with two equations in the f-annotations.

(4.68) *did* V * (↑PRED) = ‘do’
(↑TNS) = PAST

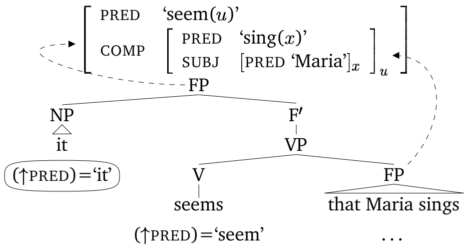
In analysis trees, the lexical f-annotations are sometimes shown below the phonological/orthographic forms for the terminal symbols (cf. (4.8)). Since they convey the morphological and lexical information, these f-annotations are called the ‘morpholexical constraints’ in Bresnan’s (2000) terminology (note that the term *constraints* is not used in the OT sense of violable constraints here). Standardly, these functional annotations are treated exactly the same way as annotations in grammar rules. This means that after instantiation of the metavariables (↑) they include, they contribute to the overall set of f-descriptions the minimal model of which is the f-structure.

As Bresnan (2000) discusses for the expletive *do*, the DEP-IO-violating use of a lexical item can be modelled by assuming that (part of) its morpholexical contribution is not actually used in the construction of the f-structure. In the examples to follow, I illustrate this by encircling the respective morpholexical constraint. The ways of checking such a violation technically are discussed in sec. 4.6.2.

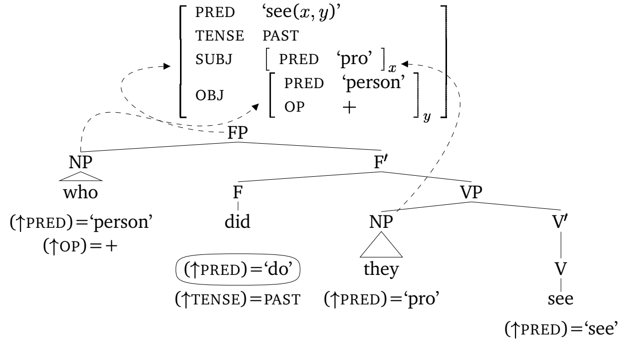
(4.69) is an example of an expletive use of the pronoun *it* in English, as assumed, e.g., in (Grimshaw and Samek-Lodovici 1998, sec. 4). (4.70) is the well-known example of the expletive *do*.[49] Note that in contrast to classical LFG, in both these cases the ordinary lexicon entry is used, i.e., referential *it*, and full verb *do*. They are just used in an unfaithful way. (In classical LFG, special lexicon entries are assumed that do not introduce their own PRED value.) In Grimshaw’s terminology this type of faithfulness violation is also referred to as a case of *unparsing* a lexical item’s lexical conceptual structure.

[49] In these examples, I use the category symbol FP for the functional categories, rather than a a concrete instance like IP. This is meant to suggest that in principle, arbitrarily many functional projections can occur in an extended projection. The structures that we actually observe arise through the interaction of markedness and faithfulness constraints.

(4.69) *Violation of* DEP-IO

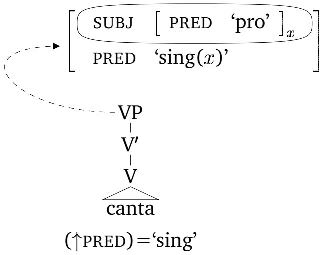


(4.70)



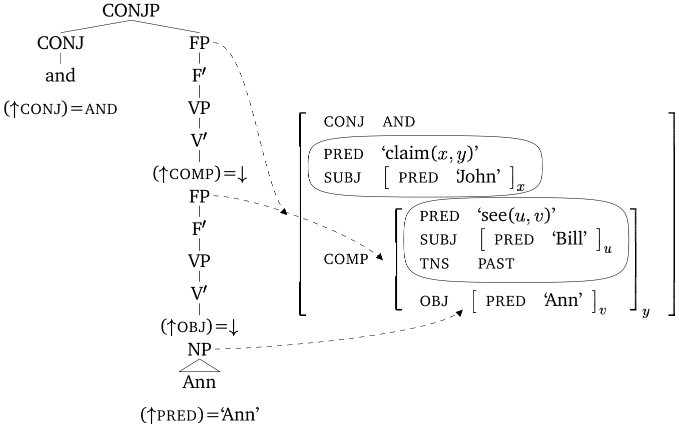
MAX-IO violations are the opposite situation. Some part of the f-structure (reflecting the input) is not being contributed by any of the lexical items' morpholexical constraints. In the examples, this is highlighted by encircling the respective part of the f-structure. (4.71) is a *pro-drop* example from Italian. Note that – again as opposed to classical LFG – the PRED value of the subject is not introduced by the inflection on the verb; it simply arises "from nothing" as a faithfulness violation.

(4.71) *Violation of* MAX-IO (3.5)



With such MAX-IO violations being part of the candidate space, it becomes conceivable to set up an OT account of ellipsis that explains the (im)possibility of ellipsis in context as an effect of constraint interaction. Let us look at the candidate (4.72) as one such MAX-IO-unfaithful candidate. It is the c-structure/f-structure analysis assumed for B's reply in dialogue (4.73).[50]

(4.72) MAX-IO-*unfaithful candidate in an ellipsis account*



[50] The representation builds on L. Levin's (1982) analysis of sluicing, assuming that at f-structure, the antecedent structure is fully reflected.

(4.73) A: John claimed that Bill saw Sue.
B: And Ann.

This example is interesting since it illustrates the need for arbitrarily large portions of dropped material (the recursive embedding in A's utterance could be arbitrarily deep, which would have to be reflected in the f-structure for B's reply, according to the account assumed here).

Note the non-branching dominance chain dominating *Ann* in (4.72). With the re-occurrence of the categories, this structure would be excluded by the offline parsability condition in classical LFG (4.14). So, if we want to model the ellipsis data with such representations, construing the amount of context-recovered information as an effect of constraint interaction, the grammar G_{inviol} defining the possible candidate analyses cannot be subjected to the offline parsability condition. This will fix the choice (4.25a) discussed in sec. 4.2.2 and 4.2.4. We get an LFG-style grammar that is not strictly an LFG grammar, producing a superset of analyses. The additional analyses do not produce any new terminal strings, but they provide strings already covered with infinitely many new f-structural interpretations (as required for the ellipsis analysis).

Giving up the classical offline parsability condition poses questions about the decidability of the processing tasks. This is discussed in chapter 6. In essence, the restricting effect of the OT constraints can be exploited to control the set of candidates that have to be effectively generated to ensure that the optimal one is among them.

Before moving on to a more rigorous formalization of faithfulness constraints, a few remarks are due on the constraint set required for the ellipsis analysis just hinted at: It is quite clear how we can make the candidate in (4.72) win over less elliptical competitors like *and that Bill saw Ann*, or even *and John claimed that Bill saw Ann*: the assumption of an Economy-of-expression constraint like *Struct outranking Max-IO will do the job – the elliptical utterance is as expressive, using less c-structural material. However, this immediately raises the question how to make sure that Economy of expression does not fire all the time, wiping out most if not all of the linguistic material. Intuitively it is quite clear that only contextually *recoverable* material may be ellided, but this idea has to be implemented more formally. A rather straightforward way is to assume a constraint Rec that is violated when some material is left unrealized without there being an antecedent in the local context (cf. Pesetsky 1998). Note that the architecture of the OT system has to be extended in order to make the extra-sentential context visible for the OT constraints (a similar modification would be required in other approaches to capture recoverability too).[51] The role that the context-representation plays in an OT analysis with arbitrary Max-IO violations is discussed further in sec. 6.3.2, under a computational perspective.

To sum up this subsection, the intuitive way of looking at the relation between the input and the candidates in OT-LFG should be as follows: What is characteristic of an individual candidate is its lexical material and c-structure; a candidate's f-structure is mostly a reflex of the input.[52] Input-output faithfulness amounts to comparing a candidate's f-structure with its morpholexical constraints. Thus one may call this the "lexicalist view of faithfulness" (cf. Kuhn 2001a).

4.6.2 The formalization of faithfulness constraints

There are various ways how the idea discussed in the previous subsection can be formalized more rigorously. Bresnan's (2000) original proposal is based on a special way of instantiating the metavariable ↑ in morpholexical constraints. Classically, all metavariables ↑ in the set of morpholexical constraints introduced by a given lexical entry have to be instantiated to the same f-structure – the one projected from the lexical item's category. For the OT-LFG model, Bresnan assumes that some of the metavariables may be instantiated by an element that does not occur in the candidate's f-structure – at the cost of a faithfulness violation. In order to facilitate the formulation of constraints according to the description-by-analysis account discussed in sec. 4.5, I proposed in (Kuhn 2001a, sec. 3.3.2) a formalization of morpholexical constraints using a special λ-projection from c-structure to a special l-structure, which I will go through in the following.[53]

[51] The condition that the Rec constraint checks for is rather complicated, so one may hope to replace it by simpler constraints, interacting. This becomes possible in a bidirectional optimization framework as discussed in chapter 5, in particular in sec. 5.3.3.

[52] In particular, faithfulness violations cannot lead to the situation that a candidate has a different meaning than the meaning encoded in the input. (Compare the discussion of the ineffability account of Legendre et al. 1998 in sec. 3.3.3 and 3.3.4, which works with LF-unfaithful winners. Ineffability is however derivable through bidirectional optimization, without assuming LF-unfaithfulness, cf. sec. 5.3.4.

[53] In a codescription account, the formulation for the Dep-IO constraint would be rather straightforward: all morpholexical constraints can be assumed to be wrapped in a two-way disjunction – either make use of the morpholexical constraint or accept a constraint violation mark. The entry for *did* would thus look as follows:

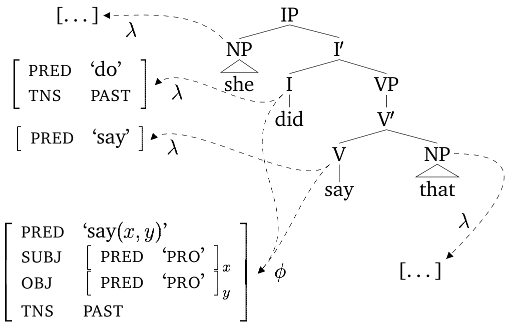
```
(i)    did   V   *   {  (↑PRED) = 'do'
                     |  *DEP-IO ∈ o }
                     {  (↑TNS) = PAST
                     |  *DEP-IO ∈ o }
```

The λ-projection-based formulation: DEP-IO

I will assume that all morpholexical constraints for a lexical item will be introduced in a separate feature structure projected from the pre-terminal node.[54] Let us call this new projection the λ-projection (for "lexical"), describing a correspondence between c-structure and "l-structure". When faithfulness is met, all elements in this set will subsume the f-structure projected from the same category; however, for unparsed morpholexical constraints, a mismatch occurs.

In (4.74), (a modification of Bresnan 2000, (44)), the idea is illustrated for an example violating faithfulness: the PRED constraint introduced by *did* does not re-appear in the f-structure.

(4.74) DEP-IO *violation (with* PRED 'do' *missing in f-structure)*



In order to reach the intended effect, the lexicon entries have to look as follows (recall that $\uparrow$ is short for $\phi(\mathcal{M}*)$ – i.e., the f-structure projected from the current node's mother, in this case the pre-terminal):

(4.75) *did* I * $(f_1\ \textsc{pred})$ = 'do'
$f_1 = \lambda(\mathcal{M}*)$
$(\ f_1 = \uparrow\ )$
$(f_2\ \textsc{tns}) = \textsc{past}$
$f_2 = \lambda(\mathcal{M}*)$
$(\ f_2 = \uparrow\ )$

say V * $(f_1\ \textsc{pred})$ = 'say'
$f_1 = \lambda(\mathcal{M}*)$
$(\ f_1 = \uparrow\ )$

For every morpholexical constraint, there are three annotation schemata, making use of a distinct local metavariable referring to a feature structure (f_1, f_2, ...). The three schemata are: (i) the lexical constraint itself,[55] (ii) an f-equation introducing the morpholexical constraint to the l-structure projected from the pre-terminal, and (iii) an *optional* f-equation introducing the constraint at the level of f-structure. The optionality of schema (iii) leads to the presence of unfaithful analyses.

The faithfulness constraint DEP-IO can now be formulated as follows:[56]

(4.76) DEP-IO
$\forall n, P.[(\textit{atomic-f-str}(\star) \wedge \textit{cat}(n) \wedge (\lambda(n)\ P) = \star) \rightarrow (\phi(n)\ P) = \star]$
"For all categories n and feature paths P, if $\star$ is an atomic value under P in the λ-projection from n, then $\star$ is also the value under P in the ϕ-projection from n."

Since the metavariable $\star$ is generally instantiated to every structural element, it is now in particular instantiated to the feature structures in l-structure. Note that the value 'do' of the PRED feature in (4.74) fails to satisfy this constraint: instantiating n as the I category and feature path P as PRED, we have $(\lambda(\mathrm{I})\ \textsc{pred})$ = 'do', but not $(\phi(\mathrm{I})\ \textsc{pred})$ = 'do'.

An issue not addressed so far is the following: What controls the choice of expletive elements (*do* rather than *shout* etc.)? This question is briefly addressed by Bresnan (2000, sec. 2), adopting the basic idea from Grimshaw (1997, 386): the assumption is that for a verb like *do*, "[t]he unparsing of its semantically minimal PRED feature is a smaller violation of faithfulness than that incurred by unparsing the semantically richer PREDs of *shout*, *obfuscate*, or any other verb in the English lexicon."

For concreteness, let us assume that this intuition is modelled by a conceptual hierarchy of PRED values – or lexical conceptual structures. More specific sub-concepts will inherit all the information from their super-concepts, plus they will add some information. Now, to evaluate faithfulness constraints on

[54] In (Kuhn 2001a, sec. 3.3.2), a *set* of feature structures was assumed in the l-structure, containing a small feature structure for each morpholexical constraint. The faithfulness constraints were then checked for each of the small feature structures. Here, I assume that the faithfulness constraints are checked for the atomic values, so it is unnecessary to assume this additional complication in the geometry of l-structure.

[55] Note that the assumption is that all constraints are expressed as *defining* equations, rather than *constraining* equations, and that Completeness and Coherence are checked only on f-structure, not on l-structure.

[56] This formulation contains a universal quantification over category nodes and features paths, as it was excluded in sec. 4.4.4. However, the domain of the variables is restricted by the (finite) lexicon, so a reformulation avoiding universal quantification would be possible.

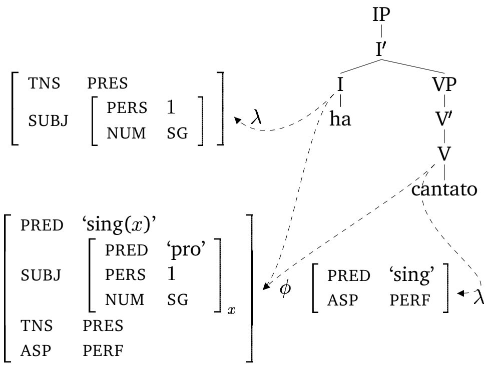
"unparsed" PRED values, the conceptual contribution they would have made is considered piece by piece, i.e., concepts embedded more deeply in the conceptual hierarchy will incur more violations than the more general ones. In effect, everything else being equal, the most general available concept will be picked as an expletive element.[57] I will not pursue this issue further in this dissertation.

The MAX-IO constraint

For the MAX-IO we get a symmetrical picture as with DEP-IO. An example is given in the structure (4.78) for (4.77). Note that none of the λ-projected (i.e., morpholexical) feature structures introduces the PRED values under SUBJ, which *does* appear in the f-structure.

(4.77) ha cantato
has sung

(4.78)



For technically "assembling" the f-structure, the grammar G_{inviol} has to provide a way of optionally introducing "pseudo-lexical constraints" for each piece of information occurring in the input. There are several ways how this could be done. One is to have a pseudo-lexical annotation in the grammar rule for the root symbol, using a functional uncertainty to reach arbitrary embedded f-structures and optionally provide some missing information, such as the PRED-value 'pro'. If we have a recursive rule for the root symbol, this way of adding information can be used over and over again:

(4.79) *Gen grammar rule,*
with the potential of providing pseudo-lexical constraints

$$\text{ROOT} \rightarrow \left\{ \begin{array}{c} \text{ROOT} \\ (\uparrow\text{GF}^{*}\ \text{PRED})=\text{`pro'} \end{array} \;\middle|\; \ldots \right\}$$

Alternatively, pseudo-lexical constraint introduction without the functional uncertainty could be foreseen for all maximal projections, by adding a recursion (this would change the c-structure representation, but the original structure can be systematically recovered if an appropriate marking is used):

(4.80) *Pseudo-lexical constraint introduction at the level of maximal categories*

$$\text{XP} \rightarrow \left\{ \begin{array}{c} \text{XP} \\ (\uparrow\text{PRED})=\text{`}\ldots\text{'} \end{array} \;\middle|\; \ldots \right\}$$

Such pseudo-lexical constraints can of course be used only at the cost of incurring a MAX-IO violation. In example (4.78), we made use of this option for the PRED-value under SUBJ. We can formalize MAX-IO as follows:

(4.81) MAX-IO
$\textit{atomic-f-str}(\star) \rightarrow \exists n, P.[\textit{cat}(n) \wedge (\phi(n)\ P) = \star \wedge (\lambda(n)\ P) = \star]$
"If $\star$ is an atomic value then there is some category n, such that $\star$ is embedded under some path P in the ϕ-projection from n and $\star$ is also the value under P in the λ-projection from n."

Again one can check that this constraint is violated in (4.78): for the value 'pro' embedded in the f-structure under the path SUBJ PRED, we do not find any category such that it is embedded in this category's l-structure under the same path as in f-structure (in particular, we do not find the value 'pro' under SUBJ PRED in λ(I)).

Conclusion

Concluding the section on faithfulness constraints, we can note that the subsumption-based conception of $Gen_{G_{inviol}}$ is indeed compatible with the idea of arbitrarily heavy faithfulness violations: the unfaithfulness arises as a tension

[57] To turn this idea into an account with reasonable empirical coverage, it clearly has to be complemented by some additional device allowing for conventionalization of the use of a particular lexical item out of a choice of semantically very similar items. For example, most Romance languages use the verb derived from Latin *habere* ('have') as a perfect auxiliary, while Portuguese uses the verb derived from *tenere* ('hold').

within the LFG candidate analyses, since the categorial/lexical structuring need not reflect the f-structure faithfully. As a consequence of this conception, even the faithfulness constraints can be checked on the candidate analyses alone, without explicit reference to the input.[58] Both types of faithfulness violations raise certain issues for the processing which will be discussed in chapter 6.

4.7 Summary

In this chapter, I proposed a formalization of OT syntax in the formal framework of LFG, elaborating the original ideas of Bresnan (1996, 2000). This formalization meets the requirements developed in chapter 3 under empirical and conceptual considerations: the cross-linguistic variance in surface realization of underlying arguments can be derived as an effect of constraint interaction. At the same time, the precondition for learnability is met, since the semantically (and pragmatically) interpreted part of the candidate representations is identical for all members of a candidate set.

This was reached by assuming non-derivational candidate analyses based on LFG's system of correspondence between parallel structures (most notably c- and f-structure). Defining possible candidate analyses as the structures produced by a formal LFG-style grammar (G_{inviol}) comprising the inviolable principles, the entire OT system can be defined in a declarative, non-derivational fashion. The only purpose of the input (or Index) is the definition of candidate sets; since the input fixes the interpretation of the candidates, the formal representation used for the input is that of a partially specified f-structure.

The formal relation between the input f-structure and the candidates in the candidate set defined by this input is subsumption. The input subsumes the candidate's f-structure, and at the same time the candidate may not specify additional semantic information. Thus, the candidates differ only in terms of c-structural information and f-structural information insofar as it is not semantically relevant (i.e., purely morphosyntactic feature information). Despite this limitation as to the degree of formal divergence between input and candidates, all empirically motivated cases of faithfulness violation can be modelled. Faithfulness emerges as a candidate-internal concept and can be checked by comparing a candidate's f-structure and the morpholexical specification of the lexical items used.

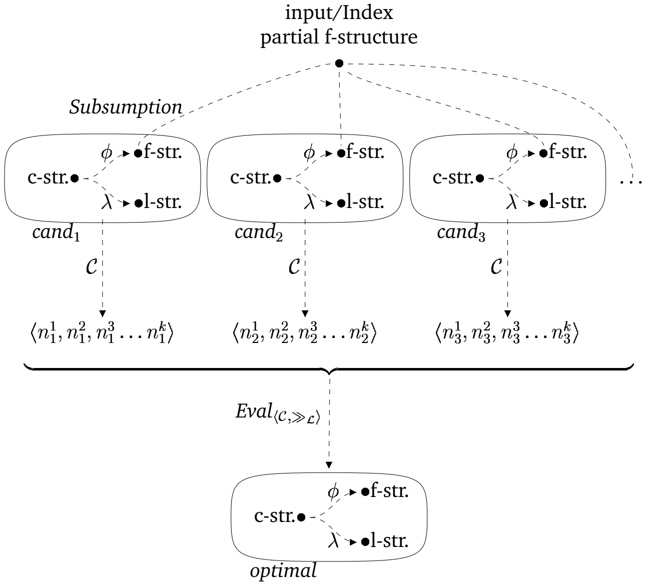
Thus, it is sufficient for both markedness constraints and faithfulness constraints to refer to the candidate structure exclusively. Constraints are formulated as schemata in a tree/feature description logic over LFG representations.

[58] Compare (Heck et al. 2000) for a similar result, and the discussion in footnote 22 on page 49.

For constraint checking/marking, the schemata are instantiated to all structural elements (c-/f-structures) in a candidate analysis. Every structural element for which a constraint is not satisfied increases the constraint violation count for this constraint. The final evaluation step based on the constraint counts for all analyses in the candidate set is the canonical harmony-based evaluation step of OT with no specific modification for the OT-LFG scenario.

The following scheme illustrates the formal setup graphically. The broken lines suggest that the relations between the formal elements making up the OT-LFG systems should be seen in a declarative way, as opposed to derivational processes.

(4.82) *The OT-LFG setup*


input/Index
partial f-structure
Subsumption
c-str.
ϕ
f-str.
λ
l-str.
$cand_1$
$cand_2$
$cand_3$
...
$\mathcal{C}$
$\langle n_1^1, n_1^2, n_1^3 \dots n_1^k \rangle$
$\langle n_2^1, n_2^2, n_2^3 \dots n_2^k \rangle$
$\langle n_3^1, n_3^2, n_3^3 \dots n_3^k \rangle$
$Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}$
optimal

Ultimately, it is important to note that the language generated by an OT-LFG system is defined with an existential quantification over underlying inputs. The definition is repeated here:

(4.24) *Definition of the language generated by an OT-LFG system* $\mathcal{O} = \langle G_{inviol}, \langle \mathcal{C}, \gg_{\mathcal{L}} \rangle \rangle$

$$L(\mathcal{O}) = \{ \langle T_j, \Phi_j \rangle \in G_{inviol} \,|\, \exists \Phi_{in} : \langle T_j, \Phi_j \rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(Gen_{G_{inviol}}(\Phi_{in})) \}$$

So, given an LFG-style grammar G_{inviol} for the inviolable principles and a set of constraints $\mathcal{C}$ with a language-specific ranking $\gg_{\mathcal{L}}$, the set of grammatical analyses is defined as those analyses $\langle T_j, \Phi_j \rangle$ produced by G_{inviol}, for which there exists an underlying input Φ_{in} such that $\langle T_j, \Phi_j \rangle$ is optimal (based on $\mathcal{C}$ and $\gg_{\mathcal{L}}$) in the candidate set defined by Φ_{in}.

Chapter 5

The direction of optimization

In this chapter, some variations of the formal setup defined in chapter 4 are discussed. Essentially, just the definition of the candidate set is altered, which in our system boils down to a change of the input. While so far in this dissertation, the input was assumed to be an underlying semantic representation, sec. 5.1 explores the use of the surface string as the input (cf. Smolensky 1996). This gives us a second optimization model. If we call the standard optimization setup we have looked at so far *production-based* or *expressive* optimization, we now get *comprehension-based* or *interpretive* optimization. Sec. 5.3 discusses various ways of combining the two to a *bidirectional optimization* model.

5.1 Varying the input to optimization

If we look at the definition of candidate generation $Gen_{G_{inviol}}$ (4.30) (repeated below), which was discussed in the previous chapter, we notice that a formally very similar function could be defined: rather than using the (partial) input f-structure as the base for comparison, we could use some part of c-structure, as in (5.1). Leaving all other components of the OT-LFG model the same, we get a formal system with very similar properties, which may however be used to model a different empirical concept.

(4.30) *Definition of **Gen***

For Φ_{in} a partial f-structure:

$Gen_{G_{inviol}}(\Phi_{in}) = \{ \langle T, \Phi' \rangle \in L(G_{inviol}) : \Phi_{in} \sqsubseteq \Phi'$, where Φ' contains no more semantic information than Φ_{in} $\}$

(5.1) *Extension of the definition of **Gen***

For w a word string:

$Gen_{G_{inviol}}(w) = \{ \langle T, \Phi \rangle \in L(G_{inviol}) \mid w$ is the terminal string/yield of T $\}$

So far, we have followed the standard application of OT as a definition of the grammatical structures of a language. What is kept constant across candidates is (more or less) the part of the structure that defines the meaning. The competing candidates are thus synonymous (potential) realization alternatives. In the procedurally flavoured standard terminology, this is called *production-based optimization*, since $Gen_{G_{inviol}}$ is in fact defined as an abstract production function. Another name is *expressive* optimization.

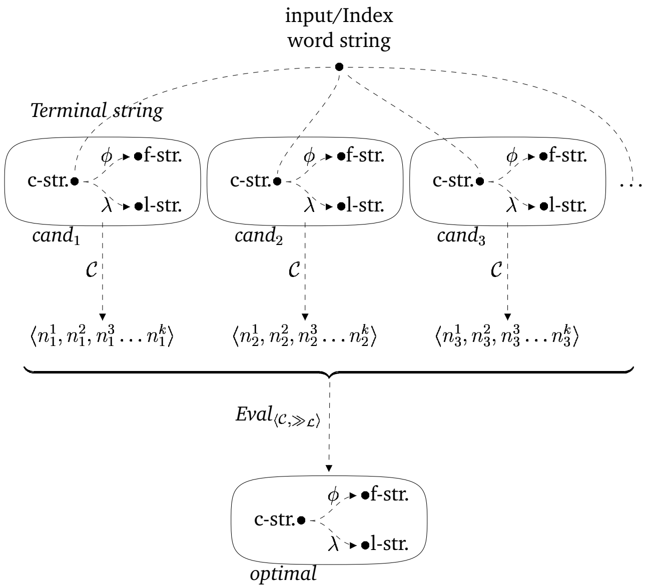
Now, we let the f-structure vary freely across candidates and rather leave the terminal string of the c-structure constant. Formally, all kinds of other criteria for specifying the candidate set are conceivable. However, in sec. 3.3 the observation was made that in order to ensure learnability, the input has to be deducible from the utterance or utterance context (formulated as restriction (3.21)).

(3.21) *Restriction on the character of the input*
All aspects of the OT input must be such that they can be in principle inferred from the general context of utterance.

For *production-based optimization*, the consequence was that only semantically and pragmatically relevant information could be included in the input (and that at the level of interpretation, all candidates had to be faithful to this information). Now, when we consider a more surface-oriented input, the learnability consideration forces us to assume a *fully* surface-detectable concept of the input. So we should assume the string of words without any fixed phrase structure representation. Definition (5.1) is compatible with this restriction.

Thus, with a string input and (5.1) as $Gen_{G_{inviol}}$, we get *comprehension-based* or *interpretive optimization*: the competing candidates are alternative parses of the same string. The scheme in (5.2) – a modification of (4.82) – shows how the mechanics of the overall system remain unaffacted when the input is changed as just argued.

(5.2) *Comprehension-based optimization in OT-LFG*


input/Index
word string
Terminal string
c-str.
ϕ
f-str.
λ
l-str.
$cand_1$
$cand_2$
$cand_3$
. . .
$\mathcal{C}$
$\langle n_1^1, n_1^2, n_1^3 \dots n_1^k \rangle$
$\langle n_2^1, n_2^2, n_2^3 \dots n_2^k \rangle$
$\langle n_3^1, n_3^2, n_3^3 \dots n_3^k \rangle$
$Eval_{\langle \mathcal{C}, \gg_{\mathcal{C}} \rangle}$
optimal

Hendriks and de Hoop (1999) use such a comprehension-based optimization model in what they call OT semantics; the winning structure models what native speakers conceive as the correct interpretation in the given context. Comprehension-based optimization is also being applied as a preference mechanism in the large-scale LFG grammars developed in the Pargram project (Kuhn and Rohrer 1997; Frank, King, Kuhn, and Maxwell 1998, 2001). Comprehension-based optimization also plays a role in learning. Tesar and Smolensky (1998) assume it as *robust interpretive parsing*. Gibson and Broihier (1998) explore to what degree such an optimization model can be used to derive disambiguation strategies in human sentence processing.[1]

Smolensky (1996) proposes to explain the lag of children's production abilities behind their ability in comprehension without having to assume a special

[1] They use special constraints modelling the *Minimal attachment* and *Late closure* strategy in an OT framework and come to the conclusion that a strict ranking of constraints is inadequate for this task (but cf. Fanselow, Schlesewsky, Cavar, and Kliegl 1999).

grammar or special processing devices. The lag is predicted by an OT system if one assumes that in comprehension a simple parsing-based optimization along the lines of (5.2) is performed, which permits processing the strings that the child hears with the same constraint ranking that is applied in production. Thus in comprehension, many analyses are accepted that are not grammatical under the child's current constraint ranking (according to the $Gen_{G_{inviol}}$-based definition of grammaticality). The simple parsing task is liberal enough not to filter them out. However in production, the common underlying structure *does* determine the candidate set, and the constraints will have a strong filtering effect. The result is a very reduced production ability for the initial constraint ranking.

In the following, I will address the question whether there are any empirical phenomena in adult language indicating that the constraint set used in production-based optimization has also an explanatory impact on comprehension-based optimization. This is done by applying a constraint set motivated independently for a production-based optimization account to the disambiguation task. Indeed, the disambiguation preferences observed for native speakers follow. The presentation follows (Kuhn 2001a, 4.2). A similar analysis of word-order freezing was proposed independently by Lee (2000, 2001), who goes into much more empirical detail than I do here. Here, I would just like to make a formal point about the OT-LFG architecture.

5.1.1 Word order freezing

With the formalization of OT-LFG, we are in a position to address the question whether constraint systems with production-based competition are necessarily distinct or even incompatible with systems designed for a comprehension-based competition. I will argue that there are phenomena where using the same constraints in both directions makes the correct empirical predictions.

The most natural interpretation of optimality in comprehension-based competition is preference of the most harmonic reading of the string. So we need to find empirical cases where the comprehension-based winner coincides with the intuitively preferred reading. It is best to look at an empirical domain which involves a fair amount of realization alternatives and ambiguity. A good example is the relatively free word order in German, modelled within OT-LFG by Choi (1999).

In the German *Mittelfeld* (the region between the finite verb in verb second position and the clause-final verb position), nominal arguments of the verb can appear in any order. However, as has been widely observed (cf., e.g., Lenerz 1977; Höhle 1982; Abraham 1986; Uszkoreit 1987), a certain "canonical" order is less marked than others (cf. also Kuhn 1995). Deviations from this canonical order are used to mark a special information structure (or topic-focus structure), i.e., these non-canonical orderings are more restricted through context. Sentence (5.3) reflects the neutral order as it would be uttered in an out-of-the-blue context. Variant (5.4a) will be used to mark *dem Spion* as the focus; (5.4b) furthermore marks *den Brief* as the topic.

(5.3)	dass	der	Kurier	dem	Spion	den	Brief	zustecken	sollte
	that	*the*	*courier* (NOM)	*the*	*spy* (DAT)	*the*	*letter* (ACC)	*slip*	*should*

(5.4) a. dass der Kurier den Brief dem Spion zustecken sollte

b. dass den Brief der Kurier dem Spion zustecken sollte

Choi (1999, 150) models these data assuming competing sets of constraints on word order: the canonical constraints, based on a hierarchy of grammatical functions (and, in principle also a hierarchy of thematic roles) (5.5); and information structuring constraints (distinguishing the contextual dimensions of novelty and prominence, each marked by a binary feature) (5.6).[2]

(5.5) CANON Choi (1999, 150)

a. CN1:
SUBJ should be structurally more prominent than (e.g. 'c-command') non-SUBJ functions.

b. CN2:
non-SUBJ functions align reversely with the c-structure according to the functional hierarchy.
(SUBJ > D.OBJ > I.OBJ > OBL > ADJUNCT)

(5.6) Information Structuring Constraints: Choi (1999, 150)

a. NEW:
A [−New] element should precede a [+New] Element.

b. PROM:
A [+Prom] element should precede a [−Prom] Element.

[2] Following more recent work (in particular by Aissen (1999)) on the OT treatment of alignment across hierarchies, the mechanism of Harmonic alignment could be used to formulate these constraints more precisely.

Based on an appropriate ranking of these constraints (Prom ≫ CN1 ≫ {New, CN2}), Choi can predict the optimal ordering for a given underspecified f-structure (which in this case will also contain a description of the informational status of the verb arguments). When the arguments don't differ in informational status – e.g., everything is *new* but nothing is *prominent* –, the canonical constraints will take effect, leading to the order in (5.3), as illustrated in the tableau (5.7), for a few sample candidates.

(5.7)

Input F-Structure:

$$\begin{bmatrix} \textsc{pred} & \text{`sollen}(x,y)\text{'} \\ \textsc{subj} & \begin{bmatrix}\textsc{pred} & \text{`Kurier'}\\ \textsc{new} & + \\ \textsc{prom} & -\end{bmatrix} \\ \textsc{xcomp} & \begin{bmatrix} \textsc{pred} & \text{`zustecken}(x,u,v)\text{'} \\ \textsc{subj} & \\ \textsc{obj} & \begin{bmatrix}\textsc{pred} & \text{`Brief'}\\ \textsc{new} & + \\ \textsc{prom} & -\end{bmatrix} \\ \textsc{obj}_\theta & \begin{bmatrix}\textsc{pred} & \text{`Spion'}\\ \textsc{new} & + \\ \textsc{prom} & -\end{bmatrix} \end{bmatrix}\end{bmatrix}$$

	Prom	CN1	New	CN2
a. ☞ der Kurier dem Spion den Brief zustecken sollte				
b. der Kurier den Brief dem Spion zustecken sollte				*
c. den Brief der Kurier dem Spion zustecken sollte		*		*

When there *are* differences in informational status, the unmarked order will however violate information structuring constraints, such that competitors with a different ordering can win out:

(5.8)

Input F-Structure:

$$\begin{bmatrix} \textsc{pred} & \text{`sollen}(x,y)\text{'} \\ \textsc{subj} & \begin{bmatrix}\textsc{pred} & \text{`Kurier'}\\ \textsc{new} & - \\ \textsc{prom} & -\end{bmatrix} \\ \textsc{xcomp} & \begin{bmatrix} \textsc{pred} & \text{`zustecken}(x,u,v)\text{'} \\ \textsc{subj} & \\ \textsc{obj} & \begin{bmatrix}\textsc{pred} & \text{`Brief'}\\ \textsc{new} & - \\ \textsc{prom} & +\end{bmatrix} \\ \textsc{obj}_\theta & \begin{bmatrix}\textsc{pred} & \text{`Spion'}\\ \textsc{new} & + \\ \textsc{prom} & -\end{bmatrix} \end{bmatrix}\end{bmatrix}$$

	Prom	CN1	New	CN2
a. der Kurier dem Spion den Brief zustecken sollte	**		*	
b. der Kurier den Brief dem Spion zustecken sollte	*			*
c. ☞ den Brief der Kurier dem Spion zustecken sollte		*		*

Like the Grimshaw/Bresnan fragment assumed in most examples so far, Choi's assumptions about *Gen* can be formulated as an LFG grammar G_{inviol}. For sentence (5.3) and its ordering variants, an application of comprehension-based optimization does not produce any interesting results, since in parsing the NPs can be unambiguously mapped to argument positions. However, if we look at sentences with ambiguous case marking like (5.9) and (5.10), the situation changes.

(5.9)

dass	Hans	Maria	den	Brief	zustecken	sollte
that	*H.* (NOM/DAT/ACC)	*M.* (NOM/DAT/ACC)	*the*	*letter* (ACC)	*slip*	*should*

(5.10)

dass	Otto	Maria	Hans	vorschlagen	sollte
that	*O.* (NOM/DAT/ACC)	*M.* (N/D/A)	*H.* (N/D/A)	*suggest*	*should*

Parsing (5.9) with the appropriate G_{inviol}-grammar will result in two classes of analyses: one with *Hans* as the subject, and *Maria* as the indirect object, and one with the opposite distribution. The latter reading is strongly preferred by speakers of German (i.e., we observe a "freezing effect"). Note that there is no way of avoiding this ambiguity with hard constraints. For (5.10), even more readings become possible: any of the three NPs can fill any of the three available argument positions. Nevertheless, speakers clearly prefer one reading. If we apply comprehension-based optimization, Choi's original constraints will predict exactly these observations: In the comprehension-based optimization the string is fixed for all competing candidates; in addition to the string, we have to assume some representation of the context which clarifies the informational status of the referents that the new sentence is about.[3] If this informational status is neutral for all referents (e.g., all are known – *not new* – and not *prominent*), the analysis which violates the fewest constraints will be the one which interprets the arguments in such a way that the observed order is in line with the canonical order. For (5.10), we will get the following competition:

[3] Some discussion of the character of such a context representation will follow in sec. 5.3.3. The representation proposed there does not immediately accommodate for Choi's representation of context, but it is not difficult to reformulate the underlying grammar and constraints in a way that has the intended effect. I do not go into these details here, since I only want to make a point about the general architecture of optimization.

(5.11)

Contextual information about set of referents: $\left\{ \begin{bmatrix} \textsc{pred} & \text{‘Hans’} \\ \textsc{new} & - \\ \textsc{prom} & - \end{bmatrix}, \begin{bmatrix} \textsc{pred} & \text{‘Otto’} \\ \textsc{new} & - \\ \textsc{prom} & - \end{bmatrix}, \begin{bmatrix} \textsc{pred} & \text{‘Maria’} \\ \textsc{new} & - \\ \textsc{prom} & - \end{bmatrix} \right\}$ *Input string:* dass Otto Maria Hans vorschlagen sollte		Prom	CN1	New	CN2
a. ☞	$\begin{bmatrix} \textsc{pred} & \text{‘sollen}(x,y)\text{’} \\ \textsc{subj} & \begin{bmatrix} \textsc{pred} & \text{‘Otto’} \end{bmatrix} \\ \textsc{xcomp} & \begin{bmatrix} \textsc{pred} & \text{‘vorschlagen}(x,u,v)\text{’} \\ \textsc{subj} & \\ \textsc{obj} & \begin{bmatrix} \textsc{pred} & \text{‘Hans’} \end{bmatrix} \\ \textsc{obj}_\theta & \begin{bmatrix} \textsc{pred} & \text{‘Maria’} \end{bmatrix} \end{bmatrix} \end{bmatrix}$				
b.	$\begin{bmatrix} \textsc{pred} & \text{‘sollen}(x,y)\text{’} \\ \textsc{subj} & \begin{bmatrix} \textsc{pred} & \text{‘Otto’} \end{bmatrix} \\ \textsc{xcomp} & \begin{bmatrix} \textsc{pred} & \text{‘vorschlagen}(x,u,v)\text{’} \\ \textsc{subj} & \\ \textsc{obj} & \begin{bmatrix} \textsc{pred} & \text{‘Maria’} \end{bmatrix} \\ \textsc{obj}_\theta & \begin{bmatrix} \textsc{pred} & \text{‘Hans’} \end{bmatrix} \end{bmatrix} \end{bmatrix}$				*
c.	$\begin{bmatrix} \textsc{pred} & \text{‘sollen}(x,y)\text{’} \\ \textsc{subj} & \begin{bmatrix} \textsc{pred} & \text{‘Maria’} \end{bmatrix} \\ \textsc{xcomp} & \begin{bmatrix} \textsc{pred} & \text{‘vorschlagen}(x,u,v)\text{’} \\ \textsc{subj} & \\ \textsc{obj} & \begin{bmatrix} \textsc{pred} & \text{‘Otto’} \end{bmatrix} \\ \textsc{obj}_\theta & \begin{bmatrix} \textsc{pred} & \text{‘Hans’} \end{bmatrix} \end{bmatrix} \end{bmatrix}$		*		*
d.	$\begin{bmatrix} \textsc{pred} & \text{‘sollen}(x,y)\text{’} \\ \textsc{subj} & \begin{bmatrix} \textsc{pred} & \text{‘Hans’} \end{bmatrix} \\ \textsc{xcomp} & \begin{bmatrix} \textsc{pred} & \text{‘vorschlagen}(x,u,v)\text{’} \\ \textsc{subj} & \\ \textsc{obj} & \begin{bmatrix} \textsc{pred} & \text{‘Otto’} \end{bmatrix} \\ \textsc{obj}_\theta & \begin{bmatrix} \textsc{pred} & \text{‘Maria’} \end{bmatrix} \end{bmatrix} \end{bmatrix}$		**		*

Thus, for the constraints that Choi (1999) assumes, the standard OT production-based view can be generalized to the comprehension-based scenario, giving rise to predictions of preferred readings that are clearly met by native speakers' intuitions.

The present discussion leaves open how exactly the comprehension-based optimization and the production-based optimization are combined. The application of both optimizations is called bidirectional optimization. I will discuss the possibilities for spelling out the combination in a rigorous way in sec. 5.3. Before this, I will address some issues about the character of comprehension-based optimization, posed by the parallelism suggested by the formal treatment.

5.2 The character of comprehension-based optimization

The formal similarity of the two optimization concepts and the prospect of deriving intuitive concepts like grammaticality and preference are intriguing. However, when the idea of comprehension-based/interpretive optimization for disambiguation is applied to a non-trivial set of data, a serious issue arises, challenging the parallelism between the two optimizations.

Although the word order freezing effect observed in sec. 5.1.1 does occur in the absence of contextual or world-knowledge clues, it can be easily overridden by such non-syntactic information. For example, take (5.12), which like (5.9) and (5.10) contains ambiguous case marking.

(5.12)	dass	diese	Oper	Mozart	komponiert	hat
	that	*this*	*opera (*NOM/ACC*)*	*M. (*NOM/ACC*)*	*composed*	*has*

Here the selectional restrictions of the verb *komponieren* 'compose' – in combination with knowledge about the argument phrases *Mozart* and *diese Oper* 'this opera' – clearly overrule the ordering preferences. The absurd reading of the opera composing Mozart does not occur to a speaker of German (neither does the sentence sound odd), even if the context has to be considered neutral. But the straightforward comprehension-based optimization account predicts the sentence to have only the odd reading.[4]

As an immediate reaction, one might try to augment the set of constraints by additional constraints taking these extra-syntactic dependencies into account.[5] Rather than developing such an account in detail, I will address some general issues raised by this move.

One general concern which I will only mention in passing is that clearly the boundaries of what is traditionally considered the scope of syntactic theory

[4] A similar influence of context and world knowledge in comprehension-based optimization is observed by Lee (2001).

[5] Müller (1998) proposes an OT account for deriving markedness judgements regarding certain word order variants in German. Working with the ordinary production-based optimization, he assumes a *subhierarchy* of constraints which is used only for determining markedness, while the matrix hierarchy is used for grammaticality. The constraints in the subhierarchy are in part based on extra-syntactic concepts like definiteness, animacy, and focus; however, no explicit reference to the actual context of an utterance is made. So the empirical predictions can only be checked against intuitions about gradual differences in markedness of isolated sentences. Since to some degree such intuitions depend on the informant's ability to make up plausible contexts, they have to be regarded with caution. The model that I will argue for in sec. 5.2.2 and demonstrate in sec. 5.3.3, assumes an explicit formal representation of context as part of the input and thus circumvents the vagueness problem in the validation of empirical predictions.

are passed when such effects of discourse context and world knowledge are incorporated into a single optimization task. *Per se*, this is neither completely new (since "pragmatic effects" on syntax have frequently been observed), nor necessarily a bad thing. Ultimately, the parallelism assumption of OT leads us to expect such a global cognitive optimization ("Parallelism: all constraints pertaining to some type of structure interact in a single hierarchy", Kager 1999, 25). However, so far, reasonable idealizations factorizing out details of the utterance context etc. have been vital for progress in linguistic theory. So one might become skeptical in case there is no way at all of pinning down the linguistic part of the problem by a suitable interface specification (this may indeed be possible as discussed in sec. 5.3.3).

5.2.1 Apparent counterevidence against constraint ranking

Let us assume we want to capture the extra-syntactic factors in disambiguation by additional constraints within comprehension-based optimization. I will concentrate on the subtask of getting the filling of the argument positions correct (this ignores other ambiguities like ambiguous tense/aspect forms, quantifier scope, resolution of definite descriptions etc.). We have to take into account at least the knowledge sources in (5.13). The inferences, based on linguistic knowledge are informally sketched by implication arrows. Examples are given below. Unless one of the knowledge types leads to an unambiguous result, one typically gets the situation of several knowledge sources interacting to lead the hearer to a particular disambiguation.

(5.13) *Knowledge sources involved in syntactic disambiguation & type of knowledge derivable*

- Phonological string
  a. word order ⇒ (information structural status of argument phrases ⇒) grammatical functions of argument phrases ⇒ argument filling
  b. morphological (head or dependent) marking ⇒ grammatical functions ⇒ argument filling
  c. intonational marking (or typographical emphasis) ⇒ information structural status of argument phrases ⇒ grammatical functions ⇒ argument filling
- Discourse context
  d. information structural status of argument phrases ⇒ grammatical functions ⇒ argument filling
  e. anaphoric dependency ⇒ semantic class of (pronominal or polysemous) argument phrases ⇒ argument filling
- Extra-linguistic context
  f. reference of deictic expressions ⇒ semantic class of argument phrases ⇒ argument filling
  g. partial disambiguation of argument filling through given situation
- Idiosyncratic/encyclopaedic knowledge
  h. selectional restrictions of the predicate ⇒ argument filling
  i. semantic class of (polysemous) argument phrases ⇒ argument filling
  j. exclusion of particular readings (encyclopaedic knowledge to the contrary)

Languages like English have word order (a.) as a fairly reliable direct source for function specification, which again allows inferences about the argument filling. In languages with a freer word order, like German, word order does not permit hard inferences, but may be an important clue, presumably via inferences about the information-structural status. We have seen case marking as an example for morphological dependent marking of grammatical function (b.), subject-verb argeement is a widespread example for morphological head marking. Intonational marking (c.) in spoken language provides clues about information-structural status (e.g., topic-marking pitch accent), which may for instance explain a certain word order, thus giving additional clues about function specification.[6]

Interacting with intonational marking, the discourse context provides clues about the information-structural status of argument phrases (d.). For instance, the second sentence in (5.14) contains ambiguous case marking of the familiar kind. With the first sentence as context, it is fairly clear that we have two predications about the same topic, *Anna Schmidt*. The noun phrase *die spätere Wahlsiegerin* will typically bear a rising accent, and the intonation contour will rise over the rest of the second sentence up to the predicate *vorgeschlagen* with a falling accent. Furthermore drawing on encyclopaedic knowledge about elections, *die spätere Wahlsiegerin* is inferred as the theme argument of *vorschlagen* 'propose'.

[6] Some discussion of such effects can be found in (Kuhn 1996a, 1996b, 1996c).

(5.14)	Anna	Schmidt	stellte	sich	einer	Kampfabstimmung
	A.	*S.*	*stood-for*	REFL	*a*	*competitive election*

Die	spätere	Wahlsiegerin	hatte	Otto	Müller	für	die	Kandidatur
The	*later*	*winner*	*had*	*O.*	*M.*	*for*	*the*	*candidacy*
vorgeschlagen								
proposed								

(5.14) contains already an example of discourse-based anaphora resolution illustrating knowledge type (e.) in (5.13): pronominals and definite noun phrases have to be resolved in order to allow inference about the semantic class of an argument phrase. Likewise, deictic phrases allow the hearer to include information from the extra-linguistic context (f.). Of course, this context may also narrow down the choice of readings (g.) (for example, it may be obvious who is the agent of a certain action).

A fairly reliable source for direct inferences about argument filling (without the reasoning via grammatical functions) is knowledge about selectional restrictions (h.). An example of this was given in (5.12), where it was clear that *compose* has to take a human being as its agent. This inference may nevertheless be distorted by polysemy of argument phrases (i.). For instance (5.15), which normally has a preference for the subject-object reading, may also have a object-subject reading in case *Mozart* is used for the works of Mozart and *diese Oper* refers to an opera house. A context for bringing out this reading would be (5.16).

(5.15)	Mozart	hat	diese	Oper	nie	aufgeführt
	M.	*has*	*this*	*opera*	*never*	*performed*

(5.16)	Unser	Haus	ist	spezialisiert	auf	die	Italienische	Oper	der	Romantik
	Our	*house*	*is*	*specialised*	*in*	*the*	*Italian*	*opera*	*of*	*Romanticism*

Most of the context-based inferences can also be made without the relevant knowledge being actually introduced in the linguistic context; in this case, the inferences are based purely on encyclopaedic knowledge ((j.) in (5.13)).

The purpose of presenting this fairly long list of knowledge types involved in disambiguation is not to start the formalizion of a particular constraint set for comprehension-based optimization. The validation of a non-trivial account of the problem would require a larger-scale computer simulation of learning based on empirical data and is thus clearly beyond the scope of this dissertation. Here, the list of knowledge types should serve as background for considerations about the general character of this comprehension-based optimization. Unfortunately, I have to stay at a rather speculative level, but hopefully this helps nevertheless in constructing the formal basis for future empirical work.

At first, it may seem as if OT with its soft constraints is ideal for modelling this interaction of uncertain knowledge. Roughly, we might model each knowledge type as a constraint, introducing violation marks for the marked options. (For example, reverse word order wrt. the functional hierarchy would be marked; likewise type coercions from individuals to their works, as we had it in the *Mozart* polysemy; for the discourse-context-sensitive knowledge, the constraint system of Beaver (2000) could be applied.) From the different interpretations of a string, the most harmonic one would then be predicted as the preferred reading.

But does constraint interaction under the OT assumptions really capture the way in which the knowledge sources are interrelated in disambiguation? What ranking should we assume for the constraints? Some sources are more reliable than others (in part depending on the language), so these should be high in the constraint hierarchy. But an important knowledge source can be overridden by a sufficient amount of lower-priority clues. This points towards a constraint *weighting* regime – contrary to OT assumptions.[7] Within a ranking regime, an additive effect could be reached only if all relevant constraints are unranked with respect to each other, which again would defeat the idea of modelling reliability by relative ranking. Having unranked constraints would also correctly predict that different knowledge sources can have a very similar effect in disambiguation.

A possible conclusion at this point might be that the two optimizations are not instances of the same formal setup (compare fn. 1 on page 119, pointing to a similar conclusion made in Gibson and Broihier 1998).

5.2.2 Optimization with a fixed context

The discussion at the end of the previous section suggested that a weighting regime of constraints might be more appropriate for comprehension-based/interpretive optimization than the ranking assumed in OT. However, this impression may well be based on an inappropriate set of assumptions in the comparison of comprehension-based and production-based optimization – i.e., not making the same idealizations in both cases.

When isolated sentences are used as examples in the judgement of interpretation preferences, there is a tendency to mix up two different optimization problems: (i) the question which is the most harmonic analysis of the string

[7] Compare also (Keller 2000; Keller and Asudeh 2001).

across all possible contexts; (ii) for a given context, which is the most harmonic analysis of the string in that context.[8] (ii) is closer to the communicative task for a hearer, but (i) constitutes the typical linguistic perspective – 'what is the preferred reading for this string?'.

Under view (i) the possible contexts are effectively *part* of what is optimized. This means that for many of the information sources listed in (5.13), only partial knowledge is available for the disambiguation task. It is uncertain which context will be the most favourable in the end. Moreover, it is unclear how the "cost" of making up a context is determined and taken into account in optimization. Thus, the linguistic problem we are interested in is overlaid by a different problem that may be the main reason for rendering so many knowledge sources uncertain and giving us the impression that the strict OT ranking mechanism is inappropriate for the task.

This may become clearer when the considerations are started from the other end: For the formal optimization problem (ii) the context is fixed, such that all candidate analyses are merely judged against this context. This should take away the need for modelling the reliability of knowledge sources – some of the constraints may now be given the same rank (or a very similar rank, cf. considerations on Stochastic OT below). So, for a particular task of type (ii) it is far more plausible to assume a constraint-ranking mechanism.

One may ask whether it is realistic in the communicative task for a hearer to know the exact context in which to evaluate the disambiguation task. There are many fine-grained facets to the representation of context in the model some of which may be unclear from the observation. So a selection of several context models may have to be considered. But it is quite intuitive that the choice between contexts should be guided by something else than the fixed-context harmony evaluation (ii) for each individual context in question: if a winner A of task (ii) is more harmonic than another winner B (for a different fixed context), this does not make the *context* included in A more plausible than the context in B. Assuming that all hard conditions on context-selection have been applied, presumably the best one can do for further narrowing-down is assume a probability distribution. So we would get a formal model with a stochastic component picking a particular context according to some empirically estimated parameters. Technically, we could assume that the unspecified parts of the input representation (which comprises the context representation in our case, since this is fixed across candidates) are filled out by a random process adhering to a probability model over possible inputs.[9] Thus, uncertainty of knowledge would be modelled outside the constraint-ranking model. (Problem (i) would be an instance of (ii) under this view, where the known context is entirely empty.)

Note that the stochastic process just sketched is of a different kind than the ones assumed in the Stochastic OT model of Boersma (1998) (although the two could be combined). Boersma assumes that the effective ranking (or disharmony) of a constraint is subject to some random noise. This is essential for the robust gradual learning algorithm (compare sec. 3.3.1 in this dissertation). For constraints that are close to each other on the ranking scale, this predicts that both ranking options can occur. In fact, the frequency distribution observed in the training data is taken up by the model.

This stochastic constraint evaluation seems exactly what is needed to make the idea more realistic that many of the knowledge sources are ranked (almost) the same. The constraints modelling these knowledge sources could indeed be ranked close to each other on the continuous ranking scale, but slight differences would nevertheless be captured.

One general remark about the character of predictions based on Stochastic OT systems should be made: for deriving a general statement like "in the linguistic context c, sentence s has interpretation i", it is inappropriate to run a single optimization for the respective input (which is perfectly sufficient in a standard OT model). Rather, what is interesting is the probability distribution of the outcome. This can be most easily estimated by sampling, i.e., running a number of optimizations of the relevant kind. For even more general statements like "sentence s has interpretation i", it should be obvious by now that such a probability distribution is more informative and empirically more adequate than a single answer for the "preferred" solution. But note that even with a given linguistic context, there is quite some space for the relevant factors in disambiguation (filling out the internal, formal concept of context), so here too a probability distribution is adequate. It shows us in which contexts a sentence is practically unambiguous and identifies particularly ambiguity-preserving contexts.

Concluding the discussion, the considerations made about the character of comprehension-based optimization are obviously preliminary. What they showed is that a straightforward application of the OT constraint-ranking model for disambiguation on real data is presumably problematic. But this does

[8] One of many deep questions here is what the "context" comprises. Clearly, the immediate linguistic discourse context is included, plus possibly some representation of the utterance situation. But yet a broader concept of context may have to be considered if we want to recast linguistic arguments in favour of linguistically possible (though implausible or semantically anomalous) interpretations of given examples (like Chomsky's 'colorless green ideas' example): frequently, it is pointed out for sentences like 'the scissors are happy' or 'my toothbrush is pregnant', that "[o]ne could, however, imagine situations in which they would be appropriate." (Steven Schaufele, LINGUIST List 7.506, `http://www.linguistlist.org/`) To capture this imaginativeness, the context would also have to include encyclopaedic knowledge; then one could access a different context in which tools can have feelings etc.

[9] The same mechanism could apply when there is some uncertainty in the interpretation of the phonetic signal.

not exclude that there is an idealization of the task isolating the linguistic part of the task and thus providing a basis for a theoretical account. I sketched one possibility of such an idealization, based on a complete "context" representation, which is assumed to be fixed across all candidates, i.e., which is technically part of the input. In order to adjust this idealization to the real disambiguation task, a different mechanism than OT could be used to control the filling out of the context representation – for instance some probability model. This would be in keeping with the OT assumptions and the methodological principle of trying to investigate the empirical scope of ranking-based constraint interaction. The part of disambiguation that is based on linguistic knowledge is modelled with a constraint ranking. (In sec. 5.3.3, I introduce comprehension-based constraint-ranking based on a fixed context; it is part of a bidirectional architecture and I show that the system permits a simplification of the constraints assumed in a unidirectional, production-based analysis of null pronouns.)

Since the original impact for considering constraint-ranking in the disambiguation task was the formal parallelism with standard production-based OT, one may object that the additional mechanisms of the fixed-context optimization model just discussed is defeating this parallelism again. However, the standard production-based OT system would also benefit from the same division of labour between a model for choosing between contexts and optimization given a context. Here, the difference between a fixed-context-based optimization and an optimization across all contexts is just less frequently distinguishable. The reason is obvious: when the input (in the old narrow sense, excluding context) is an underlying semantic representation rather than a phonological string, many more of the context-dependent factors are fixed.

But for certain discourse-dependent phenomena, such as word ordering based on information structure, we note that OT accounts like the one by Choi (1999) (addressed in sec. 5.1.1 above) have been relying on an input containing contextual information: The [+/− New] and [+/− Prom] marking of arguments, assumed to be encoded in the f-structure, reflects this assumption. Without this marking in the input, the non-canonical word order would be predicted to be ungrammatical (since it is less harmonic than the canonical order, which would be in the same candidate set). The selection of the correct context is typically not discussed for this production-based optimization since for determining grammaticality, it suffices that there exists some input (including the relevant context representation) such that the analysis is optimal for that input. The actual language production task from an underlying message (for which the determination of the correct context representation, given the utterance context, does play a role) is not of primary interest under the perspective of linguistic theory.

So the putative non-parallelism between production-based and comprehension-based optimization may arise from a number of differences in perspective, which are mainly a consequence from the methodological fact that traditionally, syntactic considerations start out from the investigation of word strings in isolation. Adjustments to this idealized approach are made when the primary concepts of grammaticality and of the correct interpretation of the sentence become incompatible with the simple model. In the case of grammaticality (production-based optimization), this has lead to the consideration of context information, but not to the question how the correct context is chosen. For the concept of the correct interpretation, the selection of the most plausible context has been intermixed with structural linguistic factors, leading to a confusing overall picture. Here, stochastic models which predict a probability distribution over interpretations should be very helpful in capturing the intuitions about preference.

5.3 Bidirectional optimization

So far in this dissertation, production-based optimization and comprehension-based optimization have been discussed in isolation (in chapters 2–4 and in sec. 5.1, respectively) or compared (sec. 5.2), but quite obviously the question arises how the two optimizations relate to each other.

If one of them models grammaticality and the other some concept of preference, we expect that they have to recur to each other. A model taking into account both directions of optimization is called a *bidirectional optimization* model. (Recall that the term *direction* should not be taken literally, which would suggest a procedural/derivational definition; the formalization in chapter 4 and the extension in sec. 5.1 showed that a strictly non-derivational/declarative formulation is possible.)

Bidirectional optimization has been argued for variously in the theoretical OT literature, on empirical and conceptual grounds (see, e.g., Wilson 2001; Boersma 1998; Smolensky 1998; Lee 2001; Morimoto 2000; Kuhn 2001a; Blutner 2000). Here, I will mainly discuss the different formal options of combining two optimization models, and the general consequences for the character of the resulting combined model. Since there are various open issues about the individual optimization models (in particular the comprehension-based one, as discussed in sec. 5.2), the considerations can have no more than a preliminary character.

5.3.1 The grammaticality/preference model and strong bidirectional optimization

Depending on the point of view, there are two combinations of production-based and comprehension-based optimization which one might call straightforward: a model which I will call here the *grammaticality/preference* model and what Blutner (2000) calls the *strong bidirectional optimization* model.

Recall the definition of the language generated by an OT system (based on the original concept of $Gen_{G_{inviol}}$, which was defined for production-based optimization):

(4.24) *Definition of the language generated by an OT-LFG system* $\mathcal{O} = \langle G_{inviol}, \langle \mathcal{C}, \gg_{\mathcal{L}} \rangle \rangle$

$$L(\mathcal{O}) = \{ \langle T_j, \Phi_j \rangle \in G_{inviol} \mid \exists \Phi_{in} : \langle T_j, \Phi_j \rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(Gen_{G_{inviol}}(\Phi_{in})) \}$$

The grammaticality/preference model

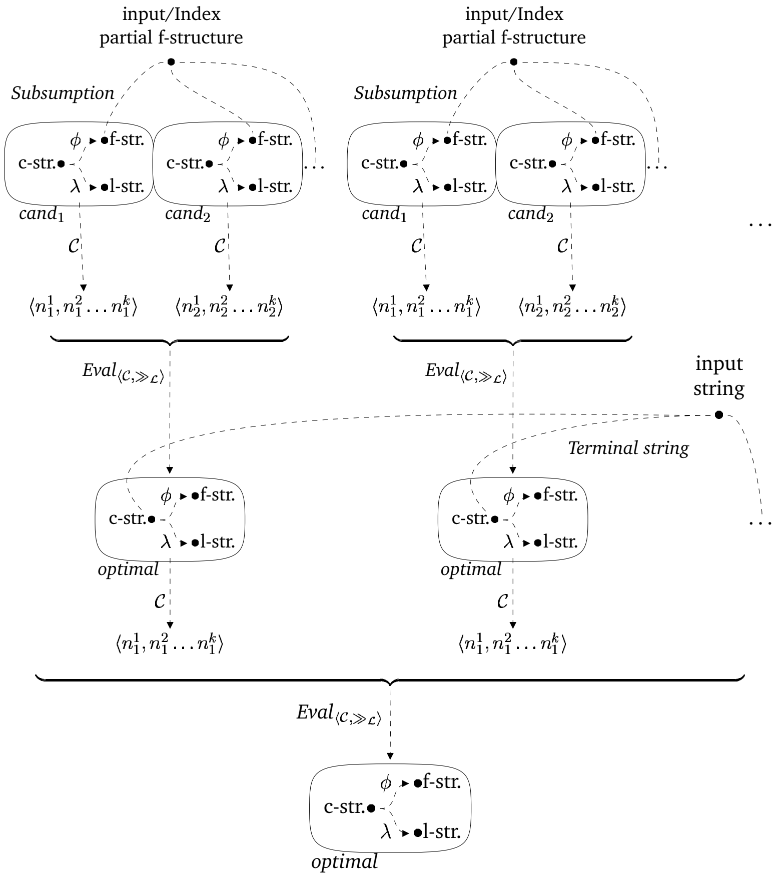
We may base the construction of a bidirectional model on the linguistic intuitions we have about the concepts being modelled by the two optimization tasks. The original production-based optimization models grammaticality, while comprehension-based optimization models preference of readings. Obviously, the latter has to be informed by the former, it is odd to assume that an analysis could be preferred that is not even grammatical. Vice versa, intuitions are different. Whether or not an analysis is grammatical should not depend on preference issues. Thus, the alternative model keeps up the old definition of the language generated by an OT system (4.24), based on production-based competition exclusively.

On top of this, the *preferred reading* of a string is then defined as the most harmonic analysis in the language with this terminal string.

(5.17) *Preferred analyses in the grammaticality/preference model*
$\langle T_j, \Phi_j \rangle$ is among the preferred analyses of a string w
iff
$\langle T_j, \Phi_j \rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(L(\mathcal{O}) \cap \{ \langle T', \Phi' \rangle \in G_{inviol} \mid w$ is the terminal string of $T' \})$

Note that here the set of analyses that is evaluated – the argument of $Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}$ – is not defined by $Gen_{G_{inviol}}$, but it is a subset of the language defined by the (production-based) OT-LFG system. The interactions are visualized in the schematic illustration in (5.18) on page 135.

(5.18) *The grammaticality/preference model*



The upper half reflects the production-based optimization underlying the definition of the language $L(\mathcal{O})$. Only the winners which contain the relevant input string are considered further on; this is indicated by the broken lines from the fixed *input string* on the right-hand side in the middle. The lower half then shows how from this (infinite) set of analyses with a particular terminal string, the preferred analysis is determined by optimization.

Strong bidirectional optimization

As an alternative to the grammaticality/preference model, strong bidirectional optimization results if one combines the optimality definitions in a conjunctive way. The idea is now that in order to be acceptable, an analysis has to be optimal in both directions. So, we depart from the original definition of grammaticality as a purely production-based notion.

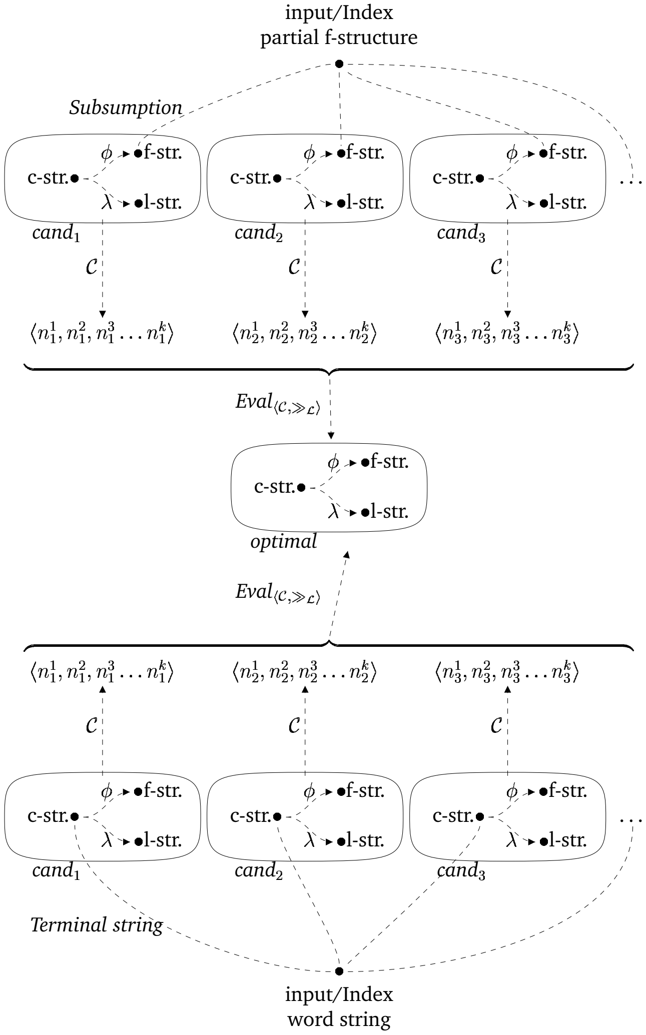
In sec. 5.1, an extended definition of $Gen_{G_{inviol}}$ was considered which generalizes to the application for both optimization directions (see (5.1)). So we can define a language consisting of those analyses that are optimal for *both* directions: (5.19). Illustrating the overall system again graphically, we get the scheme (5.20) on page 137. Note the independence and symmetry of the two optimizations.

(5.19) *Language generated by a strong bidirectional OT system* $\mathcal{O} = \langle G_{inviol}, \langle \mathcal{C}, \gg_{\mathcal{L}} \rangle \rangle$

$$
\begin{array}{ll}
L_{2/strong}(\mathcal{O}) = & \\
\quad \{ \langle T_j, \Phi_j \rangle \in G_{inviol} \mid & \exists \Phi_{in} : \langle T_j, \Phi_j \rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(Gen_{G_{inviol}}(\Phi_{in})) \\
 & \textit{and} \\
 & \exists w : \langle T_j, \Phi_j \rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(Gen_{G_{inviol}}(w)) \; \}
\end{array}
$$

The strong bidirectional OT system is more restrictive than the grammaticality/preference model: assume we are analyzing an input string w and we have some analysis A_1 (with w as its terminal string) that is optimal for some underlying input. Now, in the strong bidirectional model this analysis A_1 may be blocked (i.e., made suboptimal, and thus inacceptable) by some analysis A_2 which itself is not optimal in production-based terms. In the grammaticality/preference model, A_2 would not be grammatical and thus it would not compete against A_1 in the comprehension-based optimization. Hence, A_1 would be predicted to be grammatical and preferred.

(5.20) *Strong bidirectional optimization in OT-LFG*


input/Index
partial f-structure
Subsumption
ϕ
f-str.
c-str.
λ
l-str.
$cand_1$
$cand_2$
$cand_3$
...
$\mathcal{C}$
$\langle n_1^1, n_1^2, n_1^3 \ldots n_1^k \rangle$
$\langle n_2^1, n_2^2, n_2^3 \ldots n_2^k \rangle$
$\langle n_3^1, n_3^2, n_3^3 \ldots n_3^k \rangle$
$Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}$
optimal
Terminal string
input/Index
word string

The independence of the two optimizations in the strong bidirectional model has the advantage that the system is conceptually rather simple (this goes along with certain computational advantages, as we will see in sec. 6.4). Strong bidirectionality also opens up a simple way of deriving Language-Particular Ineffability, a phenomenon discussed in sec. 3.3.3 which poses a problem for standard unidirectional OT (recall that the assumption of LF-unfaithful candidates made by Legendre et al. (1998) is highly problematic from a learnability point of view). In strong bidirectional OT, all those underlying forms are predicted to be ineffable for which the production-based winner is suboptimal in the comprehension-based optimization (A_1 from the example just discussed is such an instance). See sec. 5.3.4 for a more detailed discussion and illustration.

The simplicity of an Ineffability analysis in the strong bidirectional model obviously excludes the danger of overgeneration that one may see for a standard production-based OT system. It is not so clear however whether this effect is reached at the price of undergeneration. Here, a problem of the independence of the two optimizations may become relevant: for every well-formed analysis one has to ensure that it comes out optimal in both directions. Without further adjustments (such as context-sensitive constraints), the strong bidirectional system predicts that ambiguity of strings is practically nonexistent. This *ambiguity problem* was first pointed out by Hale and Reiss (1998). But even a system with context-sensitive constraints, which could in principle resolve the ambiguity problem, requires much further research. With the enforced context-dependence of the comprehension-based optimization discussed in sec. 5.2, there is at least a practical problem for strong bidirectional OT: the constraint system taking context-effects into account must be extensive for a non-trivial grammar fragment.

A related potential disadvantage of strong bidirectionality is that due to the mutual independence, no interaction between the optimizations can be exploited for explanatory purposes. Thus, the inherent idea of constraint interaction as the main explanatory device is defeated at the interface of the two directions. If interaction effects across the two optimization directions *are* allowed, this can simplify the constraint systems considerably, as will be discussed in the following subsection.

5.3.2 Weak bidirectional optimization

Perhaps most problematic about the strong concept of bidirectionality is the strict blocking effect that any analysis exerts which is optimal in one of the directions. The grammaticality/preference model is weaker and incorporates the strict blocking effect only for production-based optimization, i.e., in the definition of grammaticality. In the comprehension-based optimization we get a relativized blocking effect, since only grammatical analyses compete. Depending how the issues about the exact character of comprehension-based optimization are resolved (cf. the discussion in sec. 5.2), such an asymmetrical model may or may not prove adequate for a more detailed disambiguation account.[10] But if we assume that in the future it will be possible to formulate the comprehension-based optimization in an empirically adequate way (relative to a fixed context), then even the grammaticality/preference model will presumably be too restrictive: Even though the blocking in the comprehension-based optimization is relativized, we do get strict blocking effects in the grammaticality-defining part of the model: non-preferred readings *will* block other candidates in the production-based optimization. This can lead to an undesired limitation of the explanatory potential of the constraint interaction mechanism.

In his OT system for lexical pragmatics, Blutner (2000) proposes a symmetrical concept of *weak bidirection* that remedies this problem. Weak bidirection is based on mutual dependence of the candidate sets. Transferred to the terminology of this dissertation, we get the following definition of a weak bidirectional OT system.[11]

(5.21) *The weak bidirectional OT system*

$$\begin{aligned}
&{O_p}^{rod}(\mathcal{O}) = \\
&\quad \{\langle T_j, \Phi_j\rangle \in G_{inviol} \,| \\
&\qquad \exists \Phi_{in} : \langle T_j, \Phi_j\rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{C}}\rangle}(\quad {O_c}^{ompr}(\mathcal{O}) \\
&\qquad\qquad \cap \{ \langle T', \Phi'\rangle \in G_{inviol} \,|\, \Phi_{in} \sqsubseteq \Phi'\} \quad)\} \\
&{O_c}^{ompr}(\mathcal{O}) = \\
&\quad \{\langle T_j, \Phi_j\rangle \in G_{inviol} \,| \\
&\qquad \exists w : \langle T_j, \Phi_j\rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{C}}\rangle}(\quad {O_p}^{rod}(\mathcal{O}) \\
&\qquad\qquad \cap \{ \langle T', \Phi'\rangle \in G_{inviol} \,|\, w \text{ is the terminal string of } T'\} \quad)\} \\
&L_{2/weak}(\mathcal{O}) = {O_p}^{rod}(\mathcal{O}) \cap {O_c}^{ompr}(\mathcal{O})
\end{aligned}$$

${O_p}^{rod}$ and ${O_c}^{ompr}$ are auxiliary languages specifying the production-based optima and the comprehension-based optima. What is crucial is the interdependence of the candidate sets: optimization in the production-based direction is performed on comprehension-based optima which have the same input f-structure; and vice versa, comprehension-based optimization is performed on

[10] Compare also Zeevat's (2000) arguments for an asymmetrical model.

[11] Without making the system sensitive to context, as discussed in sec. 5.2.2, the application of such a system to the syntactic domain is not very satisfactory. For comparability, I nevertheless keep to the format of the definitions given so far, i.e., ignoring context-dependence of the analyses.

production-based optima with the same string. Ultimately, the language generated by a weak bidirectional system is the intersection of the two auxiliary notions.[12]

Impressionistically, one may envisage optimization according to this concept as an inductive process, alternately running production-based and comprehension-based optimization (this will be clarified further with an example in sec. 5.3.3). If a candidate wins in both directions, it is an acceptable option for the language modelled and is removed from the candidate sets for further induction steps; thus, candidates that could not win under strong bidirection can become winners after their competitor has been retracted. Blutner argues that this concept is useful for deriving partial blocking effects in lexical pragmatics (for example the fact that *cause to die* has an indirect-causation interpretation, since the structurally simpler expression *kill* exists for the direct interpretation). So far, there has been little empirically oriented work elaborating the details of such an account. But the concept seems very appealing for the derivation of various aligment scales (cf. also Beaver 2000). In the following I discuss null subjects as an example from syntax suggesting an analysis based on weak bidirectionality.

5.3.3 Deriving recoverability through bidirectional optimization

Null subjects

Recall from sec. 3.2.3 the discussion of null subjects in Italian, based on the OT analysis of Grimshaw and Samek-Lodovici (1998) and Samek-Lodovici (1996). As the example in (5.22) illustrates in some more detail, the subject is dropped in Italian when it is coreferent with the topic of the preceding sentence: in (5.22a), *Gianni* is the subject and thus the topic, so in (5.22b), no pronoun appears. In (5.23) however, *Gianni* is the focus or within the focus of the first sentence (the topic being *la mostra* 'the exhibition'). So (5.23b) is ill-formed with a null subject.

[12] Concerns that the notion of weak bidirectionality may not be well-defined, due to the apparent circularity, are refuted by Jäger (2000). A recursive definition is possible, since the harmony relation, on which the application of *Eval* is based, is transitive and well-founded (Jäger 2000, sec. 2). Jäger also proves that the results of (Frank and Satta 1998; Karttunen 1998) – that in regular-language based OT systems, the entire system is a regular relation – carry over to weak bidirectionality.

(5.22) a. Questa mattina, Gianni$_i$ ha visitato la mostra.
this morning G. has visited the exhibition

b. Più tardi, ϵ_i/?egli$_i$/??lui$_i$ ha visitato l'università.
more late (he)/he has visited the university

(5.23) a. Questa mattina, la mostra è stata visitata da Gianni$_i$.
this morning the exhibition was visited by G.

b. Più tardi, *ϵ_i/egli$_i$/lui$_i$ ha visitato l'università.
more late (he)/he has visited the university

Grimshaw and Samek-Lodovici (1998) derive these facts with the three constraints (5.24) in an ordinary comprehension-based optimization. Parse is a different formulation for our constraint Max-IO. To avoid terminological confusion, I will keep to the terminology of this dissertation, calling the constraint Max-IO.

(5.24) (Grimshaw and Samek-Lodovici 1998, 194)

a. DropTopic
Leave arguments coreferent with the topic structurally unrealized.
Failed by overt constituents which are coreferential with the topic.

b. Subject
The highest A-specifier in an extended projection must be filled.
Failed by clauses without a subject in the canonical position.

c. Parse
Parse input constituents. Failed by unparsed elements in the input.

The ranking Grimshaw and Samek-Lodovici (1998) assume for Italian is the following:

(5.25) DropTopic $\gg$ Max-IO [or Parse] $\gg$ Subject

Furthermore assuming that the topicality status of the pronominal's antecent is encoded in the input, we get the following tableau for *ha cantato* ('he has sung') – as a simplified version of the second sentence in (5.22) (candidate b., which is maximally Max-IO-unfaithful to the input is called the *null parse*).

(5.26) (Grimshaw and Samek-Lodovici 1998, 202)

Input: $\langle \mathrm{cantare}(x), x = \text{topic}, x = \text{lui}\rangle$	DropTopic	Max-IO [or Parse]	Subject
a. ☞ ha cantato		*	*
b.		*!*	
c. lui ha cantato	*!		
d. ha cantato lui	*!		*

Candidates c. and d. violate DropTopic, since the subject pronoun is coreferent with the topic, but nevertheless realized in these candidates. Since the DropTopic outranks the faithfulness constraint Max-IO, candidate a. with the unexpressed subject pronoun is thus most harmonic.

When the subject pronoun is not coreferent with the topic (as in (5.23)), candidates c. and d. satisfy DropTopic, so their faithfulness to the input pays off this time, and c. becomes the winner:[13]

(5.27) (Grimshaw and Samek-Lodovici 1998, 203)

Input: $\langle \mathrm{cantare}(x), x = \text{lui}\rangle$	DropTopic	Max-IO	Subject
a. ha cantato		*	*
b.		*!*	
c. ☞ lui ha cantato			
d. ha cantato lui			*

For English, Grimshaw and Samek-Lodovici (1998) assume the ranking Max-IO ≫ DropTopic ≫ Subject. Hence, the effect of DropTopic is neutralized by the faithfulness requirement, and no null subjects are predicted.

[13] Candidate d. may only win if an additional constraint AlignFocus is assumed, ranked between Max-IO and Subject. With the subject marked as focus, only d. will satisfy this constraint and thus win.

Deriving recoverability from constraint interaction

The constraint DropTopic that Grimshaw and Samek-Lodovici (1998) assume is a very effective constraint, but its formulation is also a fairly complex. It contains a condition checking the discourse status of a pronoun's antecedent – within the antecendent's sentence; and sensitive to this condition the non-realization of the argument is rewarded.

Following the discussion in chapter 2 and sec. 3.1, such a constraint poses two questions: (i) is there an independent motivation and (ii) is the constraint really primitive, given its complex logical structure? (Cf. also the commitment to logically simple constraints in Grimshaw 1998.) To answer question (i): What could be a functional motivation for leaving underlying material unexpressed? At first this seems to thwart the most basic communicative principles. But it can be reconstructed straightforwardly from economy principles. To keep utterances brief, it is essential to avoid unnecessary structure. Of course, economy can only be complied with to the degree that the content of the utterance can still be conveyed. In other words, only material that can be easily reconstructed by the hearer should be dropped. This is exactly what the constraint DropTopic specializes on: avoid the repetition of (a certain type of) material that is already contextually given. So there *is* independent motivation. But, addressing question (ii), is the constraint really a primitive one?

I would like to argue that in a bidirectional optimization model, the interaction of communicative forces just discussed as a way of motivating DropTopic can be captured more perspicuously as an instance of constraint interaction, based on simpler constraints. As an additional point, this derivation of the effect of DropTopic is to demonstrate the independence of this interaction from the faithfulness constraint Max-IO (or Parse). Even with a low-ranking Max-IO, we can get a language that does not allow null subjects. This is important since else, we would have very limited possibilities of explaining ellipsis phenomena in non-*pro-drop*-languages as an effect of constraint interaction (involving Max-IO too).

The economy principle can be formulated as a constraint *XP (5.28). With this constraint, the basic pattern favouring null subjects is very simple (5.29) (note the low ranking of Max-IO).

(5.28) *XP
Avoid structure. Violated by maximal projections.

(5.29)

Input: $\langle c^{\text{antare}(x)}, x = \text{lui}\rangle$	*XP	SUBJECT	MAX-IO
a. ☞ $[_{\text{IP}}$ ha $[_{\text{VP}}$ cantato$]]$	**	*	*
c. $[_{\text{IP}}$ $[_{\text{NP}}$ lui$]$ ha $[_{\text{VP}}$ cantato$]]$	***!		

Candidate a. wins over c. simply because it contains less structure. For English, we would have SUBJ ≫ *XP, so c. would win. This pattern alone certainly does not give us the correct results. It predicts that the null parse (5.26b) is even more harmonic than a., and it does not predict any difference between the topic context (5.22) and the non-topic context (5.23).

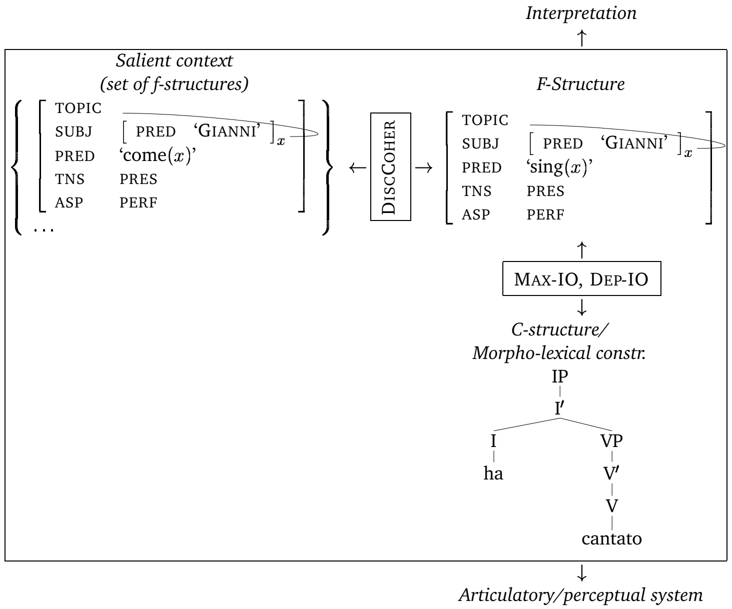
The intuition is that material can only be dropped as long as it is contextually recoverable. One way of formalizing this intuition would be to limit the candidate generation function $Gen_{G_{inviol}}$ accordingly, assuming a *recoverability principle*. Then the null parse would no longer appear in the tableaux, and the two tableaux (5.26) and (5.27) would differ in that a. would be missing from the latter one.

However, the recoverability effects can be explained by assuming a comprehension-based optimization which complements the production-based part just sketched. (Subsequently, I will focus on the problem of topic/non-topic context, leaving aside the null parse problem; once the context problem is solved, a generalization to the null parse problem follows.)

To make the bidirectional optimization explicit, we need an architecture with a representation of context. For making the case, I will here assume a very simple context representation: a set of the f-structures of the sentences in the salient context. Of course, what is actually required is some discourse semantic representation, for instance a discourse representation structure (cf. Kamp 1981; Kamp 1990; Kamp and Reyle 1993). It is essential that we have discourse referents for the individuals that can be referred to, rather than syntactic representations of surface phrases. But to avoid notational overhead, I will pretend that we can use the PRED value 'Gianni' in the f-structure as a discourse referent that is anchored to the individual the speaker and hearer know by the name Gianni.

As a further simplification I will assume that the feature TOPIC in the f-structure represents exactly the relevant information-structural notion (which is not quite true for LFG's actual discourse function TOPIC – this is the grammaticalized version of the information-structural notion).

(5.30) *Architecture for a simple context-dependent OT model*



A discourse coherence constraint DISCCOHER checks the f-structure of the currently uttered sentence against the salient context. Finding a good formulation for this constraint is not trivial, but for our purposes, the very simple formulation in (5.31) one will do. In Italian, DISCCOHER is ranked above *XP.[14]

(5.31) DISCCOHER
For atomic f-structure values in the current f-structure, the current f-structure and an f-structure from the salient context set contain the same feature path.

[14] Presumably this ranking must hold universally, but it should not be required to stipulate this fact; a re-ranking would lead to an absurd system, which should be precluded by the learning scheme.

Coreference with topic: null subject

Consider the following simplified version of dialogue (5.22):

(5.32) a. Gianni è venuto.
G. has come

b. Ha cantato
has sung

We want to derive that in this context, the null subject in the second sentence is correct. In a symmetrical bidirectional system, we have to check the following: is *ha cantato* the optimal way of expressing the underlying content *sing*(*Gianni*)? And vice versa, is *sing*(*Gianni*) the optimal interpretation of the string *ha cantato*? Ignoring the null parse at this point, this turns out straightforward in the given context. The relevant optimizations are shown in (5.33) and (5.34) below.

(5.33) *Production-based optimization*

Context	*Input F-Structure*	DiscCoher	*XP	Subject	Max-IO
{ [TOPIC SUBJ [PRED 'Gianni']$_x$ PRED 'come(x)' TNS PRES ASP PERF] . . . }	[TOPIC SUBJ [PRED 'Gianni']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]				
a. ☞	[$_{\text{IP}}$ ha [$_{\text{VP}}$ cantato]]	*	**	*	*
b.	[$_{\text{IP}}$ [$_{\text{NP}}$ lui] ha [$_{\text{VP}}$ cantato]]	*	***!		

For the production-based optimization (5.33), DiscCoher takes no effect, since both the f-structure input and the context are fixed, and so all candidates incur the same DiscCoher violations (every informative utterance will violate discourse coherence to a certain degree). Thus, as in (5.29), economy gives us *ha cantato* as the winner.

(5.34) *Comprehension-based optimization*

Context	*Input String*	DiscCoher	*XP	Subject	Max-IO
{ [TOPIC SUBJ [PRED 'Gianni'] PRED 'come(x)' TNS PRES ASP PERF] . . . }	ha cantato				
a. ☞	[TOPIC SUBJ [PRED 'Gianni']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]	*	**	*	*
b.	[TOPIC SUBJ [PRED 'Maria']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]	**!	**	*	*
c.	[SUBJ [PRED 'Maria']$_u$ PRED 'claim(u, v)' COMP [TOPIC SUBJ [PRED 'Gianni']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]$_v$]	**!*. . .	**	*	***

In comprehension-based optimization (5.34), different interpretations of the string *ha cantato* compete. For the syntactic markedness constraints (*XP and Subject), these candidates will all have the same constraint profile, since the string is fixed.[15] We do get differences in the Max-IO violations, as candidate c. shows: this candidate assumes that the string is elliptical for *Maria claimed that Gianni has sung*. So the amount of material left unrealized in the c-structure/l-structure varies with the interpretation assumed as underlying in the candidates. Note however that the number of violations of DiscCoher is decisive for the outcome. Here, candidate b. is closest to a., assuming a different referent for the unexpressed subject. However, since *Gianni* is the topic in the context, candidate a. incurs fewer violations of DiscCoher.[16]

[15] Generally, of course different syntactic analyses are possible for a given string, but here we may assume that all analyses other than [$_{\text{IP}}$ ha [$_{\text{VP}}$ cantato]] are wildly more marked.

[16] Strictly speaking, the candidate set contains also candidates with a more heavily unfaithful c- and l-structure. This way *ha cantato* can in fact be combined with an f-structure that is 100% coherent with respect to the context. Given the high ranking of DiscCoher such a candidate is the actual winner of this optimization. However, as soon as the opposite optimization direction is considered, the irrecoverability of them becomes obvious. I ignore these candidates in this

Taking together the two directions of optimization (5.33) and (5.34), we get the clear prediction that *ha cantato* is the correct form in the context under discussion.

Coreference with non-topic: overt subject

Let us now investigate the alternative context, with *Gianni* not being the topic in the previous sentence. We want to predict that a null subject is inacceptible in that context.

(5.35) a. Questa mattina, la mostra è stata visitata da Gianni.
this morning the exhibition was visited by G.

b. *ϵ/lui ha cantato
(he)/he has sung

We get (roughly) the following context representation in (5.36). Note that *la mostra* 'the exhibition' is marked as the topic.

(5.36) $$\left\{\begin{array}{l}\left[\begin{array}{ll}\text{TOPIC} & \\ \text{SUBJ} & \left[\text{PRED ‘EXHIBITION’}\right]_y \\ \text{PRED} & \text{‘visit}(x,y)\text{’} \\ \text{OBL} & \left[\text{PRED ‘GIANNI’}\right]_x \\ \text{TNS} & \text{PRES} \\ \text{ASP} & \text{PERF}\end{array}\right] \\ \ldots\end{array}\right\}$$

This time, the assumption of a weak bidirectional model proves essential. Recall that the candidate sets in weak bidirectionality are defined by mutual reference to the opposite concept of optimality. Abstractly, one should think of all dependencies as applying simultaneously. But if we want to verify the predictions we are forced to proceed in some sequence. This means that initially, we can only work with *preliminary* candidate sets, which are potentially too large since some candidates may not actually be optimal in the opposite direction (in fact, very many of them will not).

Let us start with comprehension-based optimization for the string *lui ha cantato*: Since the subject is realized, there is a smaller space of possibilities for filling out the missing part (the coreferent element has to be third person masculine). And although due to the different context, the discourse coherence is now lower than it was in (5.34), we get candidate a. – *sing*(*Gianni*) – as a clear winner.[17]

exposition, since it is more illustrative to demonstrate the irrecoverability with more intuitive examples.

(5.37) *Comprehension-based optimization* – preliminary candidate set

Context $\left\{\begin{array}{l}\left[\begin{array}{ll}\text{TOPIC} & \\ \text{SUBJ} & \left[\text{PRED ‘EXHIBITION’}\right]_y \\ \text{PRED} & \text{‘visit}(x,y)\text{’} \\ \text{OBL} & \left[\text{PRED ‘GIANNI’}\right]_x \\ \text{TNS} & \text{PRES} \\ \text{ASP} & \text{PERF}\end{array}\right] \\ \ldots\end{array}\right\}$	*Input String* lui ha cantato	DISCCOHER	*XP	SUBJECT	MAX-IO
a. ☞	$\left[\begin{array}{ll}\text{TOPIC} & \\ \text{SUBJ} & \left[\text{PRED ‘GIANNI’}\right]_x \\ \text{PRED} & \text{‘sing}(x)\text{’} \\ \text{TNS} & \text{PRES} \\ \text{ASP} & \text{PERF}\end{array}\right]$	**	***		
b.	$\left[\begin{array}{ll}\text{SUBJ} & \left[\text{PRED ‘MARIA’}\right]_u \\ \text{PRED} & \text{‘claim}(u,v)\text{’} \\ \text{COMP} & \left[\begin{array}{ll}\text{TOPIC} & \\ \text{SUBJ} & \left[\text{PRED ‘GIANNI’}\right]_x \\ \text{PRED} & \text{‘sing}(x)\text{’} \\ \text{TNS} & \text{PRES} \\ \text{ASP} & \text{PERF}\end{array}\right]_v\end{array}\right]$	***!...	***		**

We might now expect that the production-based optimization will confirm *lui ha cantato* as optimal for *sing*(*Gianni*). This is not the case however. Without the specially tailored DROPTOPIC constraint, there is nothing substantial that makes competition (5.38) (for the non-topic context) different from (5.33) above (for the topic context).

(5.38) *Production-based optimization* – preliminary candidate set

Context $\left\{\begin{array}{l}\left[\begin{array}{ll}\text{TOPIC} & \\ \text{SUBJ} & \left[\text{PRED ‘EXHIBITION’}\right]_y \\ \text{PRED} & \text{‘visit}(x,y)\text{’} \\ \text{OBL} & \left[\text{PRED ‘GIANNI’}\right]_x \\ \text{TNS} & \text{PRES} \\ \text{ASP} & \text{PERF}\end{array}\right] \\ \ldots\end{array}\right\}$	*Input F-Structure* $\left[\begin{array}{ll}\text{TOPIC} & \\ \text{SUBJ} & \left[\text{PRED ‘GIANNI’}\right]_x \\ \text{PRED} & \text{‘sing}(x)\text{’} \\ \text{TNS} & \text{PRES} \\ \text{ASP} & \text{PERF}\end{array}\right]$	DISCCOHER	*XP	SUBJECT	MAX-IO
a. ☞	$[_{\text{IP}}$ ha $[_{\text{VP}}$ cantato]]	**	**	*	*
b.	$[_{\text{IP}}$ $[_{\text{NP}}$ lui] ha $[_{\text{VP}}$ cantato]]	**	***!		

[17] The same proviso as in footnote 16 on page 148 applies.

Had we assumed a strong bidirectional model, this would be a problem. Since the two optimizations do not agree on a single f-structure/string pair, the underlying input f-structure would be predicted to be ineffable under the ranking for Italian.

In a weak bidirectional model we are not finished yet however. We do not know yet whether we were initially using the correct candidate sets for the two optimizations. So we have to check whether (5.38a) really should have been in the candidate set for the respective underlying input f-structure (i.e., *sing*(*Gianni*)). For this to be the case, *sing*(*Gianni*) would have to be optimal for the string of (5.38a) – *ha cantato* – in the present context. This comprehension-based competition is checked in (5.39).

(5.39) *Comprehension-based optimization* – preliminary candidate set

	Context	*Input String*	DiscCoher	*XP	Subject	Max-IO
	{ [TOPIC SUBJ [PRED 'EXHIBITION']$_y$ PRED 'visit(x, y)' OBL [PRED 'GIANNI']$_x$ TNS PRES ASP PERF] . . . }	ha cantato				
a. ☞	[TOPIC SUBJ [PRED 'EXHIBITION']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]		**	**	*	*
b.	[TOPIC SUBJ [PRED 'GIANNI']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]		***!	**	*	*
c.	[TOPIC SUBJ [PRED 'MARIA']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]		***!	**	*	*

This competition starts out similar to (5.34), but note the difference in the context. For this reason, *Gianni* is no longer the most coherent choice for filling out the subject. It is more coherent to use the topic of the previous sentence as the subject, i.e., the exhibition. So we have found an instance of irrecoverability: in the present context, *sing*(*exhibition*) is optimal for *ha cantato* and vice versa.[18] This shows that (5.38a) is not contained in the candidate set (5.38), according to weak bidirectional optimization and we get b. as the winner of the corrected tableau:

(5.40) *Production-based optimization* – corrected candidate set

	Context	*Input F-Structure*	DiscCoher	*XP	Subject	Max-IO
	{ [TOPIC SUBJ [PRED 'EXHIBITION']$_y$ PRED 'visit(x, y)' OBL [PRED 'GIANNI']$_x$ TNS PRES ASP PERF] . . . }	[TOPIC SUBJ [PRED 'GIANNI']$_x$ PRED 'sing(x)' TNS PRES ASP PERF]				
b. ☞	[$_{IP}$ [$_{NP}$ lui] ha [$_{VP}$ cantato]]		**	***!		

Hence we have a match between the two directions of optimization (5.37) and (5.40): in the non-topic context, *lui ha cantato* is predicted to be the correct form for *sing*(*Gianni*)).

Note finally, that although the null subject analysis incurs a Max-IO violation, this constraint is neither involved in deriving the right context effects, nor in the cross-linguistic contrast with non-*pro-drop*-languages like English (English follows if Subject outranks *XP). This is desirable since it leaves space for ellipsis analyses in non-*pro-drop*-languages.

The argumentation in this section showed several things:

- the constraint set assumed by Grimshaw and Samek-Lodovici (1998) for the analysis of null subjects can indeed be simplified by moving to a bidirectional optimization model: the complex formulation of the DropTopic constraint is no longer required;
- in a bidirectional optimization account, the interaction between constraints and the directions of optimization derive the concept of *recoverability*, which is usually assumed as a meta-restriction on syntactic analyses;
- optimization based on a fixed context permits a fine-grained account of the empirical data, while at the same time working with highly general constraints (using the same constraint set for both directions);

[18] This means that the actual prediction for the data in (5.35) and (5.23) is the following: the null subject version of the second sentence (in both examples) is not syntactically ungrammatical, but it has the semantically anomalous reading in which the exhibition is the agent of an action. (Compare also footnote 8 on page 130 above.) This seems a reasonable account of the data.

- finally, the notion of weak bidirectionality (as opposed to the straightforward strong model) is crucial for such an account.

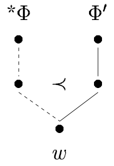
5.3.4 Ineffability and strong vs. weak bidirectionality

As pointed out briefly in sec. 5.3.1, a bidirectional OT model provides a solution to the puzzle that Language-Particular Ineffability poses to the OT approach (cf. sec. 3.3.3) without recurring to the assumption of LF-unfaithful candidates (as Legendre et al. (1998) do).[19] Recall that LF-unfaithful candidates are problematic from the point of view of learnability (sec. 3.3.4).

Ineffability and strong bidirectionality

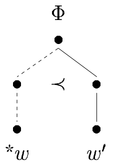
With strong bidirectionality, the mechanism that makes a certain logical form ineffable in a particular language is quite straightforward: only meaning-form pairs that are optimal in both directions are defined to be included in the language of the OT system. Now, suppose the optimal candidate for a certain underlying representation Φ has surface string w. But in the comprehension-based optimization of the alternative candidate analyses with string w, we get a different winner: some candidate with the underlying form Φ' ($\Phi' \neq \Phi$). This means that Φ is ineffable in that language. One may say that this meaning is irrecoverable for the hearer since she must always assume that when a speaker utters w he means Φ'. In other words, Φ' blocks Φ, making Φ ineffable. We can illustrate this by the following schematic picture (following a visualization scheme of Johnson 1998); I use the * on an f-structure representation to mark ineffability and $\prec$ for the less-harmonic-than relation:

(5.41)



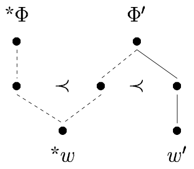
Note that ungrammaticality and ineffability are exact mirror images in a strong bidirectional model: Ungrammaticality of a string w results if the optimal among all analyses for a string w has the underlying form Φ, but in production-based optimization for Φ we get an optimal candidate with a different surface string w' ($w' \neq w$). So, w' blocks w, making w ungrammatical.

(5.42)



With the simplicity of blocking configurations, it is easy to see that we can have a situation where an underlying form Φ is blocked by an alternative reading Φ' of string w, which is itself ungrammatical due to another string w' for Φ'. String w may for example be a multiple *wh*-question like *Who ate what*, which is ungrammatical in Italian, with the underlying multiple *wh*-question (Φ) being ineffable. An alternative interpretation of *Who ate what*, with an indefinite object (Φ'), blocks Φ. The string w itself is blocked by a different string w' – the Italian equivalent of *Who ate anything*.

(5.43)



For the present purposes it is of subordinate relevance what exact constraints are involved in giving rise to the sketched harmony relation among the candidates. The following *ad hoc* interpretive constraints under ranking $C^1 \gg_{\mathit{Italian}} C^2$ would for instance have the intended effect of making Φ' more harmonic than Φ:

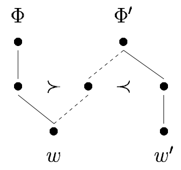
(5.44) a. C^1: non-topicalized pronouns get an indefinite interpretation

b. C^2: *what* is interpreted as a *wh*-word

In English, the opposite constraint ranking would lead to a different picture, with both the form-meaning pair $\langle w, \Phi\rangle$ and $\langle w', \Phi'\rangle$ being well-formed:

[19] This application of bidirectional optimization was brought to my attention by Joan Bresnan (p.c., March 2000). The same general idea is underlying in the proposal by Smolensky (1998) (see also the application of bidirectional OT-LFG in Lee 2001).

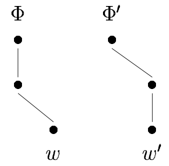
(5.45)



Ineffability and weak bidirectionality

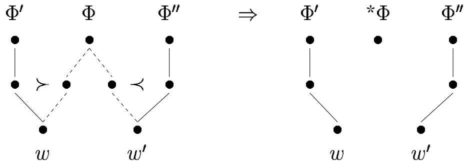
How can ineffability be modelled in the weak bidirectional model discussed in sec. 5.3.2 and 5.3.3? The direct blocking account of the strong model does not carry over, since with weak bidirectionality the unoptimal candidates of the first round may "get a second chance". As the bidirectional winners are removed from the preliminary candidate sets, losers of a strong bidirectional competition may still become winners under the weaker regime. For the picture in (5.43), we would for instance exclude the $\langle w, \Phi \rangle$ candidate from the preliminary candidate set of w: since we know that the optimal form for Φ, we can be sure that w cannot be its optimal form too.

(5.46)



But this would change the situation in such a way that $\langle w, \Phi \rangle$ is predicted to be bidirectionally optimal too – both in English and Italian. This shows that with weak bidirectionality a more sophisticated account of ineffability is required. An underlying representation will be predicted to be ineffable only if all possible realizations are bidirectionally optimal for some other representation, as sketched in the schematic picture in (5.47) (with preliminary candidate sets on the left and the final candidate sets – singletons – on the right). The competition for the ineffable meaning Φ ends up with an empty candidate set since all preliminary candidates turned out to be optimal for some other meaning.

(5.47)



Note however that all *strings* in the original preliminary candidate set for Φ are predicted to be grammatical (with some other meaning). This poses an empirical problem for ineffability examples like the Italian **Who ate what*. Of course, the context-sensitive set-up proposed in sec. 5.3.3 provides further means to derive the inacceptability of examples – all possible contexts may be semantically anomalous –, but we have to note that the strong bidirectional model allows for a more elegant account of Language-Particular Ineffability. Hence, both the strong and the weak model have conceptual and empirical advantages and disadvantages; clearly more research is required before one can decide which one should be favoured – or how a third alternative should look like, combining the advantages of both.

Interestingly, some of the computational considerations in the following chapter will depend on design decisions in the bidirectionality question too.

5.4 Summary

In this chapter I discussed various issues around the directionality question in a formal OT model of syntax. At this point it would be premature to draw any definite conclusions. A striking observation is that although the formal means make it straightforward to define a comprehension-based optimization in analogy to the standard production-based model, it is fairly intricate to judge whether the behaviour of such a system is in line with linguistic intuitions. Future work has to clarify the character of the individual optimizations and their combination further.

Sec. 5.3.3 showed however that the context-oriented application of a weak bidirectional model gives rise to a very promising account of syntactic phenomena in context. The analysis uses a set of well-motivated constraints with a simple structure, deriving the recoverability condition on syntactic structures as an effect of constraint interaction. On the other hand, sec. 5.3.4 revealed advantages of a strong bidirectional OT model in the derivation of Language-Particular Ineffability. The decision between the two types of bidirectionality has to be considered open and will require further research.

Chapter 6

Computational OT syntax

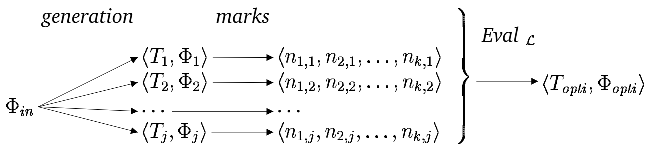
In this chapter, I address the computational side of the OT syntax formalization. The main issues, to be reviewed in sec. 6.1, are the infinity of the candidate set and directionality of processing. As we have seen in sec. 4.2.2, unrestricted OT systems are undecidable in the general case; i.e., it may be undecidable whether a given string is in the language generated by such a system. Here, I will argue however that the conceptually and empirically well-motivated formalization of chapter 4 provides a sufficiently restricted basis for a computational account. In sec. 6.2, I show that decidability results on LFG generation can be extended to the OT-LFG model and discuss the consequences for the other processing tasks. Sec. 6.4 presents a chart-based algorithmic approach to generation and parsing.

6.1 Processing issues for OT-LFG

Given the formal OT-LFG system defined in chapter 4 and the generalization to the other direction of optimization discussed in chapter 5, can one devise computational procedures for tasks like recognition, parsing and generation? Here, I will mainly look at the individual unidirectional models, addressing the question of bidirectional models only in passing (but I will come back to bidirectionality in sec. sec:decid-OT-other). Let us start considerations with the simpler task, first of all the generation task for a production-based optimization system: given an underlying form (an input f-structure), what is the optimal candidate according to an OT system? I will call this task (A1).

The initial idea how to approach this task is quite obvious: we could follow the definition of the OT-LFG system illustrated in (4.82) on page 115, using standard LFG processing techniques: (i) generate from the input f-structure, using the LFG grammar G_{inviol} for inviolable principles; (ii) apply constraints to the candidates (this gives us a sequence of constraint violation counts for each candidate); (iii) pick the most harmonic candidate:

(6.1)


generation
marks
Eval $_{\mathcal{L}}$
Φ_{in}
$\langle T_1, \Phi_1\rangle$
$\langle T_2, \Phi_2\rangle$
$\dots$
$\langle T_j, \Phi_j\rangle$
$\langle n_{1,1}, n_{2,1}, \dots, n_{k,1}\rangle$
$\langle n_{1,2}, n_{2,2}, \dots, n_{k,2}\rangle$
$\dots$
$\langle n_{1,j}, n_{2,j}, \dots, n_{k,j}\rangle$
$\langle T_{opti}, \Phi_{opti}\rangle$

The parsing task with a comprehension-based optimization system is symmetrical (see (5.2) on page 119). I will call this task (B1). For a computational account the same set-up suggests itself, only starting with a string and applying standard LFG parsing rather than generation as the initial step.

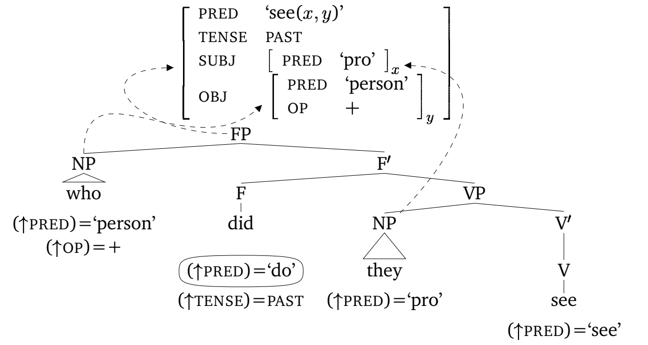
Now the question is: Are these obvious computational approaches possible with the system formalized in chapter 4? The crucial issue is whether the faithfulness violations allowed by $Gen_{G_{inviol}}$ can be dealt with computationally.

6.1.1 Infinite candidate sets in processing

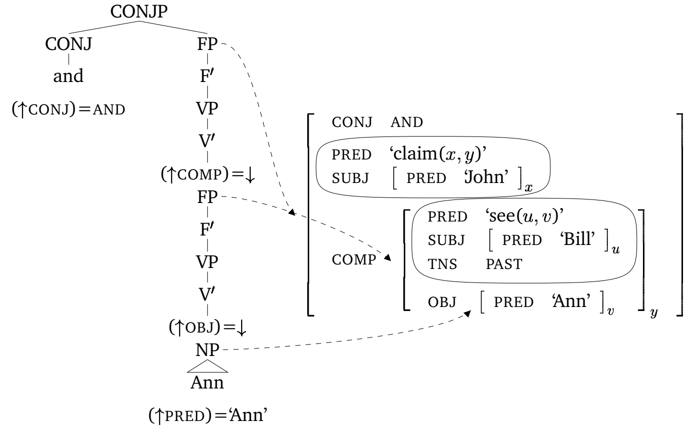
For each of the two directions of optimization, one of the faithfulness constraints is a processing issue (when violated). For convenience, (4.70) and (4.72) are repeated as examples of unfaithful analyses (details of the λ-projection based representation of sec. 4.6.2 are irrelevant here).

DEP-IO violations – epentheses – like (4.70) can create an infinite number of possibilities for generation with a production-based optimization (task (A1)): As the notation using the general category symbol FP for the functional projection suggests (cf. footnote 49 on page 105), the c-structure rules in G_{inviol} allow us to stack arbitrarily many functional projections in an extended projection. Furthermore, the f-structure contribution of all of them can be unified, since we can ignore the PRED values (under a DEP-IO violation). In other words, candidate [$_{\text{FP}}$ who did [$_{\text{FP}}$ did [$_{\text{VP}}$ they see]]] is available too for the same input f-structure as in (4.70), etc. So, according to the OT inuitions we get indeed infinitely many candidates. And this is certainly true for any input. Note that in the (A1) generation task MAX-IO violations – deletions – like (4.72) are no problem, since there is only a finite amount of information in the input to delete.

(4.70) *Violation of* DEP-IO



(4.72) MAX-IO-*unfaithful candidate in an ellipsis account*



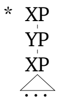
For the (B1) task – parsing with a comprehension-based optimization – the situation is the mirror image. MAX-IO violations create an infinite number of possibilities, as suggested by candidate (4.72), which may be used in an ellipsis analysis. Here, DEP-IO violations are unproblematic, as there is only a finite number of string elements that could have been inserted.

(Against the background of the context-oriented setup of a bidirectional OT system discussed in sec. 5.3.3, one expects that deep stacking of repeated MAX-IO violations is empirically more relevant than repeated DEP-IO violations. But there should be a general way of deriving the effects from constraint interaction.)

Given that the formalization of OT syntax is based on the LFG formalism, why does the infinity problem not arise in classical LFG parsing and generation? Here, the details in the interpretation of G_{inviol} as a "formal LFG-style grammar" (sec. 4.2.1 and 4.2.2) come into play. The bare LFG formalism – the combination of a c-structure grammar as an unrestricted context-free grammar and f-structure projected from c-structure – does actually allow for an infinite number of different structures over a given terminal string: if the context-free grammar contains a rule recursion that can be used in a non-branching way, there are arbitrary many c-structures, including zero to n recursions. To ensure decidability of the parsing task, such recursions are excluded in LFG by definition: the offline parsability condition (Kaplan and Bresnan 1982, 266) basically says that if there is a potential recursion in a nonbranching chain, the structure passing this recursion zero times is the only valid LFG structure (see (6.2a), which was briefly discussed in sec. 4.1 on page 60).

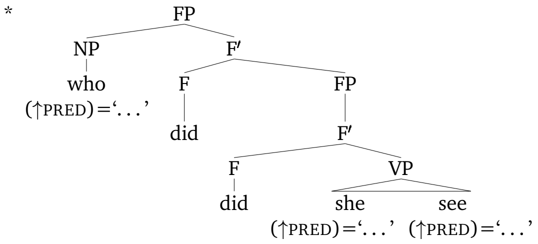
For the classical generation task (see Wedekind 1995; Wedekind 1999; Kaplan and Wedekind 2000), there is a parallel issue to take care of: in a unification-based framework, the same feature information can arise from arbitrary many c-structural places, all being unified together. To guarantee decidability of the generation task, an *offline generability* condition has to be assumed, again excluding vacuous application of rule recursion, here with reference to resourced feature structures (cf. the example in (6.2b), assuming that *did* does not introduce a resourced PRED value).[1]

(6.2) a. *Parsing*



[1] The use of an offline generability condition is currently explored by the XLE group at Xerox PARC (John Maxwell, p.c., July 2000). The idea is that recursive parts of the grammar may only be passed if some resourced – or instantiated – feature (e.g., a PRED value) is introduced along the way.

b. *Generation*



Now, coming back to OT processing, there is a choice:

- One could decide to inherit the favourable computational properties of the standard LFG model and define G_{inviol} to be an LFG grammar in the narrow sense, including the offline parsability and offline generability condition. So, in certain cases the computed candidate set would be restricted *a priori*, where the formal OT model actually predicts restriction through constraint interaction. But note that this does not exclude the possibility of faithfulness violations altogether. It merely excludes repeated faithfulness violations based on a single rule recursion. So, empirically this restriction might go unnoticed – at least for the DEP-IO violations in the (A1) task.

  For all practical purposes involving the implementation of non-trivial fragments, this is presumably the adequate choice, in particular as it means that existing parsing/generation systems like XLE can be applied straightforwardly.

- Alternatively, G_{inviol} could be defined as a more relaxed formal grammar than a classical LFG grammar. The limiting effect of constraint interaction on the degree of unfaithfulness would then have to be reflected in the processing system too. This computational account would meet the methodological principle (3.1) of constraint interaction as *the* explanatory device also in the processing approach. Thus this choice is superior on theoretical and aesthetic grounds. For practical application on a larger scale, it is presumably less adequate.

  To be able to control the constraint profile of an infinite set of candidates, one needs an approach with interleaved candidate generation and constraint checking. The sequential set-up (6.1) cannot work, since the first step would not terminate. Such a procedure, using a chart for generation and parsing, is proposed in (Kuhn 2000b) (discussed here in sec. 6.4). The construction in sec. 6.2 also builds on this insight.

6.1.2 Directionality in processing

Independent of the decision on the formal character of G_{inviol}, discussed at the end of the previous section, there is a further processing issue that either of the approaches has to address. This is introduced in the current subsection.

So far, we have looked at procedures for

(A1) the generation task for production-based optimization (typically modelling grammaticality); and – symmetrically –

(B1) the parsing task for comprehension-based optimization (typically modelling preference).

This leaves open important other tasks. With (A1), we have the generation task for production-based optimization, but the respective parsing and recognition task is still missing: we want a procedure telling us whether a given *string* is contained in the string language defined by the OT model (the recognition task). We may also want to know what the correct structure for this string is, which is what Johnson (1998, sec. 4) calls the *universal parsing task*.[2] Recognition and parsing (for production-based optimization) are closely related. Let us refer to both tasks as (A2).

According to the definition of the language generated by an OT system ((4.24) on page 66), the (A2) tasks amount to checking whether there is *some* underlying input representation for which the string is the optimal candidate.[3] In parsing, we are typically interested in all possible analyses, so the task is to find *all* underlying input representations which have the given string as the terminal string of the optimal candidate.

At this point it is probably already clear that the (A2) task is crucially different from (B1) – although both tasks are parsing tasks (for more discussion see (Johnson 1998) and (Kuhn 2001a, sec. 4.1)): in the formal model underlying (B1), comprehension-based optimization, it is the string that defines the candidate set; hence, when we are given a particular string, it is straightforward to compute the corresponding candidate set $Gen_{G_{inviol}}(w)$ by parsing with G_{inviol} and then apply harmony evaluation on the analyses. In contrast to this, the formal model underlying the (A2) task is production-based. So, grammaticality can only be determined with an f-structure-based candidate set. When we are given a string w, we first have to find underlying input f-structures Φ_j which could have defined the candidate sets $Gen_{G_{inviol}}(\Phi_j)$ that made an analysis with string w optimal. So, although (A2) is the parsing task for production-based OT, the crucial step is a generation step, very much like in (A1): the generation from underlying f-structures gives us the set of candidates on which the constraints are applied.

How do we arrive at the possible underlying f-structures Φ_j (for which the generation task will be computed)? Since input f-structures subsume candidate f-structures it suffices to look for those analyses in G_{inviol}, which have string w as their terminal string. From these candidates' f-structures we can extract the relevant input information. So, given our string w we are looking for the set $\{\langle T_j, \Phi_j\rangle \in G_{inviol} \,|\, w \text{ is the terminal string of } T_j\}$. This is in fact a parsing task quite similar to the initial step of (B1), but recall that it will be followed by (A1)-style "backwards" generation steps to complete the (A2) parsing task.

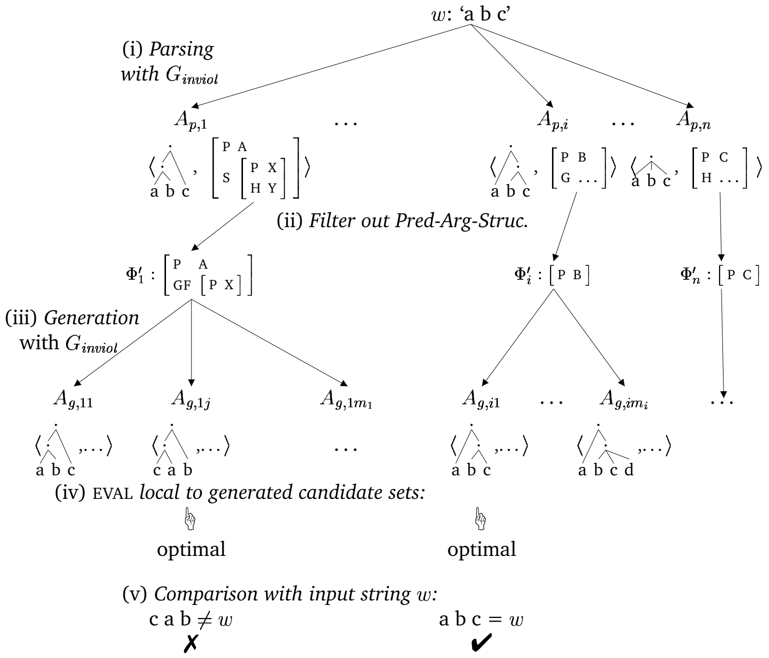
The scheme in (6.3) on page 164 (taken from Kuhn 2001a) illustrates the entire (A2) process graphically for an abstract example (parsing the string 'a b c'). Note that a given string may have no or many grammatical readings. Quite obviously, a computational procedure for task (A2) along these lines involves processing in two directions, so one may call it a *bidirectional processing* approach. However one should not confuse this with the concept of bidirectional *optimization* models. Note that optimization is applied only in one direction. One could of course apply another optimization at the very end of the procedure sketched in (6.3), comparing the strings that survive the comparison step (v). This extended procedure would then model the bidirectional grammaticality/preference model of sec. 5.3.1, sketched in (5.18) on page 135. So rather interestingly, the implementation of this simple bidirectional model adds nothing to the complexity of the processing task – neither does it reduce the complexity. If a strong bidirectional model (as sketched in (5.20) on page 137) is implemented, the processing task actually becomes simpler: one can apply comprehension-based optimization already during the parsing step (i), so only the optimal candidate's underlying form has to be considered for step (iii)-(v). (For instance, the parse $A_{p,1}$ in (6.3) may be optimal for step (i), then (ii), (iii) and (iv) would only have to be applied to this candidate, and failure of the comparison (v) would tell us immediately that the string parsed is not well-formed according to strong bidirectional optimization.)

[2] Johnson's definition is:

(i) *The universal parsing problem for OT-LFG:*
Given a phonological string s and an OT-LFG G as input, return the input-candidate pairs $\langle i, c\rangle$ generated by G such that the candidate c has phonological string s and c is the optimal output for i with respect to the ordered constraints defined in G.

[3] For comprehension-based optimization (B), the parallel task – (B2) – is intuitively less interesting (given a logical form, is it the preferred reading for some string in the language under consideration?). I will thus focus on the (A2) task.

(6.3) *Task (A2) as parsing and "backward generation"*



(i) parse string to determine possible candidates with the string

(ii) filter out the part of the candidates' f-structure that reflects the input

(iii) "backward generation" from input f-structures

(iv) harmony evaluation: optimal candidate in a generation-based competition determines grammaticality

(v) string in optimal candidate has to match the initial string; else, initial string is not grammatical for this particular underlying input f-structure

But let us go back to the (A2) task, i.e., parsing for a unidirectional, comprehension-based optimization model. To close off this section let us come back to the issue of unfaithful candidates discussed in sec. 6.1.1. There I noted that only DEP-IO violations are problematic for the (A1) task. So one might have thought that production-based optimization can be modelled computationally without worrying about unpleasant side-effects of MAX-IO violations (e.g., for null subjects or ellipsis).

But implementing (A1) alone is not sufficient, since this task does not tell us for a given string whether it is contained in the language of the OT system; the recognition/parsing task (A2) *is* required. And with (A2) we *do* get the issue of MAX-IO violations for the comprehension-based optimization model too. Formally, there is an infinite set of possible candidates for each given string, so step (i) from (6.3) may not terminate.

Of course the problem does not arise if G_{inviol} is defined as a strict LFG grammar, since then offline parsability guarantees that the set of analyses for a given string is finite. Hence, task (A2) is not problematic in principled terms. With the alternative choice however (unrestricted G_{inviol}), the situation is more intricate. In the direction of optimization (generation for (A1) and (A2)), we have the possibility of exploiting constraint interaction for controlling the degree of unfaithfulness. This possibility is missing for the opposite direction, i.e., parsing in (A2). This issue is discussed in more detail in the following section.

6.2 Decidability of OT-LFG generation

In this section, I show that the OT-LFG formalization established in chapter 4 provides a sufficiently restricted basis for a computational account. Sec. 6.2.1 reviews the result of Kaplan and Wedekind 2000, which establishes that the result of standard LFG generation (from a given fully specified f-structure) can be constructed as a context-free grammar. In sec. 6.2.2, I exploit this result to show that the generation for a production-based OT-LFG system (task (A1) from sec. 6.1) is decidable. Sec. 6.3 will discuss the consequences for the remaining processing tasks.

6.2.1 Generation with LFG grammars

The result of Kaplan and Wedekind 2000 – that LFG generation produces context-free languages – constitutes the crucial ingredient for the decidability argument for OT-LFG I will make in the following section. Before going into Kaplan and Wedekind's construction, I will briefly review some of the longer-established results on decidability of generation with LFG grammars.

Decidability of LFG generation from fully specified f-structures

Wedekind (1995) proves the decidability of generation from *fully* specified f-structures; in contrast, Wedekind (1999) presents a proof that generation from f-structures which are only partially specified is undecidable in the general case (see also Dymetman 1991). However, as Wedekind (1999, 280f) discusses briefly, it seems that undecidability arises only with certain non-linguistic grammars in which "semantic" features are used that are structurally unrelated to the remaining f-structure representations and where arbitrarily large portions of recursive f-structure can trigger a single "semantic" feature distinction. The use of features for encoding underlying semantic forms in natural language grammars is more limited: the semantic features will always correspond to some non-recursive portion of other f-structure information in a way defined by the grammar. This property will guarantee that generation from such a semantic feature structure, lacking a full f-structure specification, is decidable after all: the size of the unknown full f-structure corresponding to a given semantic representation is bounded by the size of the semantic representation multiplied with a constant factor determined by the grammar; thus, in adding f-structure features to the underspecified feature structure, only a bounded space of structural possibilities has to be checked against the grammar.

What remains to be established is a straightforwardly checkable criterion that a grammar has to satisfy in order to be sure that the semantic features are well-behaved.[4] A safe (though presumably overrestrictive) criterion is to allow underspecification only for those input features which have a finite range of values. From such mildly underspecified input f-structures it is very easy to get to generation from fully specified input f-structures: filling in all combinations of possible values for the unspecified features leads to a finite set of f-structures; so for each of these, generation from fully speficied f-structures can be performed. The overall result is then the union of all individual generation results.

The (Kaplan and Wedekind 2000) paper is also based on the assumption that no underspecification beyond this mild type is allowed in generation from f-structures. (Anticipating the application in OT-LFG candidate generation, note that this restriction is generally unproblematic: as argued at length in chapter 4, all candidates share the same interpreted part of f-structure, which directly reflects the input. Thus, only morphosyntactic features may be added in candidate generation – an example might be the declension class feature of adjectives in German. Note that such features generally have a finite range of values.[5])

[4] As discussed in sec. 6.1.1, an offline generability condition to this effect is being explored in ongoing work (see footnote 1 on page 160 in particular).

[5] Of course, l-structure (sec. 4.6.2) has to be taken into account too. Under a DEP-IO violation, it is possible that l-structure material occurs in a candidate that is not contained in the input f-structure. Note however that such additions can only occur in lexical insertion. Thus the range of possibilities is restricted by the size of the lexicon. Since each lexicon entry has a finite set of "lexical constraints" (i.e., lexical f-annotations), and there is a finite lexicon, the set of possible l-structure extensions for a given f-structure is (large but) finite. So the decidability of candidate generation is not affected. (Note that this means that productive word formation has to be triggered by the input f-structure, so it can also be based on a finite set of building blocks.)

LFG generation as the construction of a context-free grammar

While the general decidability results for LFG generation have been established for some time, Kaplan and Wedekind (2000) provide a new perspective on the generation problem, which proves very fruitful for the understanding of candidate generation and constraint interaction in OT-LFG.

In an LFG generation task, we have given an LFG grammar, including a lexicon, and a particular ("input") f-structure. The problem is to find the set of strings s such that the grammar assigns an LFG analysis $\langle T, \Phi \rangle$ to s, with s the terminal string of T and Φ the "input" f-structure[6] that is being generated from. The innovation of Kaplan and Wedekind (2000) is to move attention somewhat away from the input f-structure, focusing on the LFG grammar that has to be able to provide an analysis for the strings we are interested in. What is effectively performed in their reconstruction of the generation task is a specialization of this LFG grammar with the outcome of getting a grammar that will not accept arbitrary strings from the original language, but only the strings that have the input f-structure as their f-structure. What makes this reconstruction so interesting is that the resulting specialized grammar is no longer a full-fledged LFG grammar (in which case the enterprise would have been quite useless), but rather a simple context-free grammar. A formal precondition for this is that the input f-structure may contain no cycles, which is a very reasonable assumption for linguistic representations.

(6.4) *Kaplan and Wedekind's construction*
Given an arbitrary LFG grammar G and a cycle-free f-structure Φ, a context-free grammar G' can be constructed that generates exactly the strings to which G assigns the f-structure Φ.

I will occasionally refer to the resulting context-free grammar as $KW(G, \Phi)$.

The context-freeness result is reached by folding all f-structural contributions of lexical entries and LFG rules into the c-structural rewrite rules. Of course, this is only possible since we know in advance the range of f-structural objects that can play a role in the derivation: they must all be substructures of the input f-structure, i.e., either the root f-structure itself, or partial f-structures

[6] I will continue using the term "input" f-structure in the following, since it seems quite suggestive, even though we are not in an OT setting presently.

that can be reached through some feature path from the root f-structure. There is a finite set of such substructures, and we know that every metavariable in the f-annotations of rules and lexicon entries in the original LFG grammar have to end up instantiated to one of these substructures.

So, Kaplan and Wedekind (2000) construct multiple copies of each LFG rule, each for a particular instantiation of the metavariables. While the general idea is quite straightforward, the details of the construction are rather sophisticated: as all f-annotations are removed in the final step, one has to make sure that all their restricting effects are mimicked by the context-free grammar, i.e., the c-structure symbols have to be specialized sufficiently to make all relevant distinctions. The presentation of the construction in the (Kaplan and Wedekind 2000) paper is rather dense; here I attempt to point out the underlying ideas and illustrate them with examples. For the exact specification, the reader is referred to the original paper.

Category specialization I will illustrate the specialization steps with a sample grammar (6.5) and lexicon (6.6). A sample analysis illustrating the use of functional projection FP in this grammar is given in (6.7).

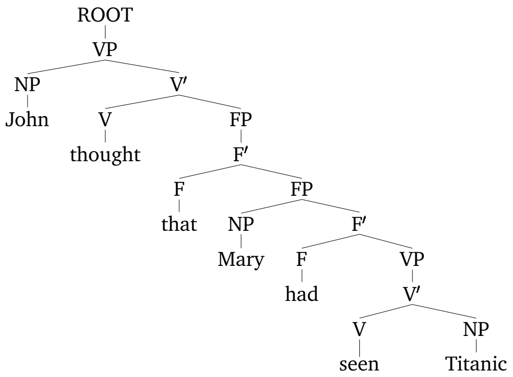
(6.5)

$$
\begin{array}{lcl}
\text{ROOT} & \rightarrow & \underset{\uparrow=\downarrow}{\text{FP}} \\[2ex]
\text{FP} & \rightarrow & \left\{ \begin{array}{cc|cc} \text{NP} & \text{FP} & (\text{NP}) & \text{F}' \\ (\uparrow\textsc{topic}) = \downarrow & \uparrow = \downarrow & (\uparrow\textsc{subj}) = \downarrow & \uparrow = \downarrow \\ (\uparrow\textsc{comp}^{*}\ \textsc{obj}) = \downarrow & & & \end{array} \right\} \\[2ex]
\text{F}' & \rightarrow & \underset{\uparrow = \downarrow}{\text{F}} \quad \left\{ \begin{array}{c|c} \text{FP} & \text{VP} \\ \uparrow = \downarrow & \uparrow = \downarrow \end{array} \right\} \\[2ex]
\text{VP} & \rightarrow & \underset{(\uparrow\textsc{subj})=\downarrow}{(\text{NP})} \quad \underset{\uparrow=\downarrow}{\text{V}'} \\[2ex]
\text{V}' & \rightarrow & \underset{\uparrow = \downarrow}{\text{V}} \quad \left\{ \begin{array}{c|c} \text{NP} & \text{FP} \\ (\uparrow\textsc{obj}) = \downarrow & (\uparrow\textsc{comp}) = \downarrow \end{array} \right\}
\end{array}
$$

(6.6)

Mary	NP	$(\uparrow\textsc{pred})=$‘Mary’ $(\uparrow\textsc{num})=\textsc{sg}$
John	NP	$(\uparrow\textsc{pred})=$‘John’ $(\uparrow\textsc{num})=\textsc{sg}$
Titanic	NP	$(\uparrow\textsc{pred})=$‘Titanic’ $(\uparrow\textsc{num})=\textsc{sg}$
that	F	
has	F	$(\uparrow\textsc{tns})=\textsc{pres}$ $(\uparrow\textsc{subj num})=\textsc{sg}$
have	F	$(\uparrow\textsc{tns})=\textsc{pres}$ $(\uparrow\textsc{subj num})=\textsc{pl}$
had	F	$(\uparrow\textsc{tns})=\textsc{past}$
see	V	$(\uparrow\textsc{pred})=$‘see$\langle\ (\uparrow\textsc{subj})\ (\uparrow\textsc{obj})\ \rangle$’
saw	V	$(\uparrow\textsc{pred})=$‘see$\langle\ (\uparrow\textsc{subj})\ (\uparrow\textsc{obj})\ \rangle$’ $(\uparrow\textsc{tns})=\textsc{past}$
seen	V	$(\uparrow\textsc{pred})=$‘see$\langle\ (\uparrow\textsc{subj})\ (\uparrow\textsc{obj})\ \rangle$’
thought	V	$(\uparrow\textsc{pred})=$‘think$\langle\ (\uparrow\textsc{subj})\ (\uparrow\textsc{comp})\ \rangle$’ $(\uparrow\textsc{tns})=\textsc{past}$
laughed	V	$(\uparrow\textsc{pred})=$‘laugh$\langle\ (\uparrow\textsc{subj})\ \rangle$’ $(\uparrow\textsc{tns})=\textsc{past}$

(6.7) a. c-structure



b. f-structure

$$\begin{bmatrix} \textsc{pred} & \text{‘think}\langle(\uparrow\textsc{subj})\ (\uparrow\textsc{obj})\rangle\text{’} \\ \textsc{tns} & \textsc{past} \\ \textsc{subj} & \begin{bmatrix} \textsc{pred} & \text{‘John’} \\ \textsc{num} & \textsc{sg} \end{bmatrix} \\ \textsc{comp} & \begin{bmatrix} \textsc{pred} & \text{‘see}\langle(\uparrow\textsc{subj})\ (\uparrow\textsc{obj})\rangle\text{’} \\ \textsc{tns} & \textsc{past} \\ \textsc{asp} & \textsc{perf} \\ \textsc{subj} & \begin{bmatrix} \textsc{pred} & \text{‘Mary’} \\ \textsc{num} & \textsc{sg} \end{bmatrix} \\ \textsc{obj} & \begin{bmatrix} \textsc{pred} & \text{‘Titanic’} \\ \textsc{num} & \textsc{sg} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Before the generation-specific conversion from LFG rules to context-free rules is performed, the generalized format of right-hand sides in LFG rules is converted to the standard context-free notation (as a kind of “preprocessing” step). So rules containing disjunctions and optionality brackets are replaced by a list of rules with simple category strings as right-hand sides. (Kleene stars, which do not appear in the sample grammar, are removed by introducing new category symbols and recursive rules. Disjunctions appearing within the f-annotations are also propagated up to the rule level.)

The result of this preprocessing step is shown in (6.8). Note that the only effect this conversion has on the resulting c-structure/f-structure analyses arises from the replaced Kleene star (and this effect can be systematically recovered from the analysis).

(6.8)	a.	ROOT	→	FP ↑=↓	
	b.	FP	→	NP (↑TOPIC)=↓ (↑COMP* OBJ)=↓	FP ↑=↓
	c.	FP	→	NP (↑SUBJ)=↓	F′ ↑=↓
	d.	FP	→	F′ ↑=↓	
	e.	F′	→	F ↑=↓	FP ↑=↓
	f.	F′	→	F ↑=↓	VP ↑=↓
	g.	VP	→	NP (↑SUBJ)=↓	V′ ↑=↓
	h.	VP	→	V′ ↑=↓	
	i.	V′	→	V ↑=↓	NP (↑OBJ)=↓
	j.	V′	→	V ↑=↓	FP (↑COMP)=↓
	k.	V′	→	V ↑=↓	

The next conversion step depends on the particular input f-structure that is being generated from. Let us assume we want to generate from the f-structure in (6.7b). This means we have five substructures: the root f-structure, plus the embedded f-structures that can be reached by the paths SUBJ, COMP, COMP SUBJ, and COMP OBJ. We know that any relevant metavariable in the rules and lexicon must end up instantiated to one of these, although we do not know yet which are the correct ones. So for each path in the f-structure, from the root f-structure to some substructure, a distinct variable is introduced that can be used in the category specialization. As the variable names, we can simply use v subscripted with the (abbreviated and possibly empty) feature path from the root f-structure, so we get the variables $v, v_s, v_c, v_{cs}, v_{co}$.

As a first augmentation of the category names, the corresponding f-structure variable is added. So for the original category FP, we get FP:v, FP:v_s, FP:v_c, FP:v_{cs}, and FP:v_{co}. In principle, the rules are multiplied out to cover all possible combinations of augmented categories. However, the combinations are restricted by the original f-annotations relating the mother's f-structure projection to each of the daughters' f-structure projection ($\uparrow{=}\downarrow$, $(\uparrow\textsc{subj}){=}\downarrow$, etc.). For the FP:$v_c$ variant of rule (6.8c), we get only NP:v_{cs} and F′:v_c, while the FP:v variant maps to NP:v_s and F′:v.

This diversification of the category symbols provides the basis for remodelling the effect of all the f-annotations in the rules and in the lexicon entries, including lexical contributions like $(\uparrow\textsc{pred}){=}$‘Mary’ or $(\uparrow\textsc{num}){=}\textsc{sg}$, as well as potential restrictions on rules with defining or constraining equations (not shown in the sample grammar). The diversified category symbols tell us what particular f-structure to assume as the instantiation of $\uparrow$ or $\downarrow$. For instance, in the NP:v_s variant of the lexicon entry for *Mary*, the f-annotation $(\uparrow\textsc{num}){=}\textsc{sg}$ is instantiated as $(v_s\ \textsc{num}){=}\textsc{sg}$, while in the NP:$v_{cs}$ variant, it surfaces as $(v_{cs}\ \textsc{num}){=}\textsc{sg}$.

It seems extraordinarily difficult to keep track of the interactions between these f-constraints within the c-structural skeleton, but Kaplan and Wedekind (2000) apply a very effective “trick”. Rather than computing the effect of the various f-constraints at intermediate levels of the tree structure, sets of instantiated f-constraints are treated as an unanalyzed part of the category names; they are then threaded through the tree in a bottom-up fashion.

So the fully diversified category name for two instances of the lexicon entry *Mary* look as follows (now written as standard context-free rules, for lexical insertion):

(6.9)
$$\begin{array}{lcl}\mathrm{NP}{:}v_s{:}\left\{\begin{matrix}(v_s\ \textsc{pred}){=}\text{‘Mary’}\\(v_s\ \textsc{num}){=}\textsc{sg}\end{matrix}\right\} & \rightarrow & \text{Mary}\\ \mathrm{NP}{:}v_{cs}{:}\left\{\begin{matrix}(v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\(v_{cs}\ \textsc{num}){=}\textsc{sg}\end{matrix}\right\} & \rightarrow & \text{Mary}\end{array}$$

The rules are again multiplied out to cover all possible combinations, with the constraint that the instantiated f-constraints of all daughters, plus the appropriately instantiated rule-specific annotations have to be unioned together to form the set of f-constraints of the mother. So, for rule (6.8g) based on the categories $\mathrm{NP}{:}v_{cs}{:}\left\{\begin{matrix}(v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\(v_{cs}\ \textsc{num}){=}\textsc{sg}\end{matrix}\right\}$ and $\mathrm{V'}{:}v_c{:}\left\{\begin{matrix}(v_c\ \textsc{pred}){=}\text{‘laugh’}\\(v_c\ \textsc{tns}){=}\textsc{past}\\v_c=v_c\end{matrix}\right\}$, we would get the rule

$$\mathrm{VP}{:}v_c{:}\left\{\begin{matrix}(v_c\ \textsc{subj})=v_{cs}\\(v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\(v_{cs}\ \textsc{num}){=}\textsc{sg}\\(v_c\ \textsc{pred}){=}\text{‘laugh’}\\(v_c\ \textsc{tns}){=}\textsc{past}\\v_c=v_c\end{matrix}\right\}\rightarrow \mathrm{NP}{:}v_{cs}{:}\left\{\begin{matrix}(v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\(v_{cs}\ \textsc{num}){=}\textsc{sg}\end{matrix}\right\}\ \mathrm{V'}{:}v_c{:}\left\{\begin{matrix}(v_c\ \textsc{pred}){=}\text{‘laugh’}\\(v_c\ \textsc{tns}){=}\textsc{past}\\v_c=v_c\end{matrix}\right\}$$

The topmost f-constraint in the VP node's set arises from instantiating the $(\uparrow\textsc{subj}){=}\downarrow$ annotation of the NP daughter: $\uparrow$ is instantiated as v_c (from VP:v_c), and $\downarrow$ is instantiated as v_{cs} (from NP:v_{cs}). The $\uparrow{=}\downarrow$ annotation of V′ in rule (6.8g) does not add an instantiated f-constraint that is not already present from the union of the daugthers.

With this bottom-up construction it is ensured that at the new categories corresponding to the root symbol of the original LFG grammar (i.e., categories of the form ROOT:v{: $\{\ldots\}$}), the full collection of instantiated f-constraints is available. The check whether or not the resulting sets of f-constraints have the input f-structure as their minimal model is effectively made external to the context-free grammar: all those variants of the original root symbol whose f-constraint union does *not* have the intended f-structure model[7] are excluded from the context-free grammar. Technically, this is done through the selective addition of rules for a new start symbol, above the original root symbol: only few rules of the form

(6.10) $\mathrm{ROOT'} \rightarrow \mathrm{ROOT}{:}v{:}\{\ \ldots\}$

are introduced to the new context-free grammar. One reason for not introducing the ROOT′ rule for a particular variant of the original ROOT symbol is inconsistency of the collected f-constraints. For instance, the combination of a third person singular subject (like *Mary*) and the auxiliary *have* goes all the way through – up to the ROOT symbol, but then the f-constraint set contains $(v\ \textsc{subj num}){=}\textsc{pl}$ from the lexical f-annotations of *have*, plus $(v_s\ \textsc{num}){=}\textsc{sg}$ from the NP, plus finally $(v\ \textsc{subj}){=}v_s$ from rule (6.8c). This set of equations is not satisfied by any model.

But even the vast majority of consistent (and complete and coherent) sets of f-constraints fails to satisfy the criterion of having exactly the input f-structures as their minimal model. This is because in the construction, contributions from the entire lexicon and all rules are combined freely, and the check is only made at the ROOT′ level. It is obvious that the purpose of this construction is not a computationally useful approach, but rather the principled solvability result (which may increase the understanding of various algorithmic approaches).

Being able to specify the result of LFG generation as a context-free grammar has the advantage that standard techniques for context-free grammars can be applied. For example, if there are infinitely many possible strings for a given f-structure, the shortest one can be produced, based on the pumping lemma for

[7] The task of determining which f-constraint sets have the intended model is decidable since the set of all possible instantiated descriptions is finite (recall that the instantiation of metavariables is limited to the substructures of the input f-structure) – i.e., there is a (large but) finite number of subsets to be checked.

context-free languages. (Essentially, the infinite number of possible solutions must be due to a recursion in the resulting context-free grammar; so, if the grammar is applied without allowing recursion, only a finite number of strings are generated.)

In the case of the sample grammar (6.8), we do indeed get infinitely many strings for the input f-structure. The grammar overgenerates in several respects. For instance, the functional projection FP can be stacked, and since the lexicon entry for *that* (as an F^0) does not contribute any PRED value it can be introduced over and over again. (If a PRED value was introduced, the several instances could not be unified, due to the instantiated symbol character of PRED values.[8]) The specialized context-free grammar contains recursions, based on rules (6.8d) and (6.8e), one example being the following (irrelevant morphosyntactic features are skipped in the f-constraints):

(6.11)

$$\mathrm{FP}{:}v_c{:}\left\{\begin{array}{c}(v_c\ \textsc{pred}){=}\text{‘see}\langle\ \ldots\rangle\text{’}\\ (v_c\ \textsc{tns}){=}\textsc{past}\\ (v_c\ \textsc{subj})=v_{cs}\\ (v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\ (v_c\ \textsc{obj})=v_{co}\\ (v_{co}\ \textsc{pred}){=}\text{‘Titanic’}\\ v_c=v_c\end{array}\right\}\to \mathrm{F}'{:}v_c{:}\left\{\begin{array}{c}(v_c\ \textsc{pred}){=}\text{‘see}\langle\ \ldots\rangle\text{’}\\ (v_c\ \textsc{tns}){=}\textsc{past}\\ (v_c\ \textsc{subj})=v_{cs}\\ (v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\ (v_c\ \textsc{obj})=v_{co}\\ (v_{co}\ \textsc{pred}){=}\text{‘Titanic’}\\ v_c=v_c\end{array}\right\}$$

$$\mathrm{F}'{:}v_c{:}\left\{\begin{array}{c}(v_c\ \textsc{pred}){=}\text{‘see}\langle\ \ldots\rangle\text{’}\\ (v_c\ \textsc{tns}){=}\textsc{past}\\ (v_c\ \textsc{subj})=v_{cs}\\ (v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\ (v_c\ \textsc{obj})=v_{co}\\ (v_{co}\ \textsc{pred}){=}\text{‘Titanic’}\\ v_c=v_c\end{array}\right\}\to \mathrm{F}{:}v_c{:}\emptyset\ \ \mathrm{FP}{:}v_c{:}\left\{\begin{array}{c}(v_c\ \textsc{pred}){=}\text{‘see}\langle\ \ldots\rangle\text{’}\\ (v_c\ \textsc{tns}){=}\textsc{past}\\ (v_c\ \textsc{subj})=v_{cs}\\ (v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\ (v_c\ \textsc{obj})=v_{co}\\ (v_{co}\ \textsc{pred}){=}\text{‘Titanic’}\\ v_c=v_c\end{array}\right\}$$

$\mathrm{F}{:}v_c{:}\emptyset$ is one of the “diversified” categories we get fot the lexicon entry *that* in (6.6), so the context-free grammar will indeed generate an arbitrary number of *that*s on top of any FP. So for the sample f-structure in (6.7b), we would get the following strings (among infinitely many others):

(6.12) a. John thought that Mary had seen Titanic.
b. John thought that that Mary had seen Titanic.
c. That John thought that Mary had seen Titanic.

[8] Technically, this effect is not brought out by the part of the construction described here, since it requires a special treatment of the f-annotations introducing instantiated symbols. Kaplan and Wedekind (2000) do not go into these details either, but they point out (fn. 2) that instantiated symbols have to receive a similar treatment as set-valued f-structures (which I skipped in the presentation above).

The effect does not depend on the emptiness of the set of f-constraints contributed by the F^0 element: since the mother’s f-constraint set is formed by set union over the daughters, adding the same f-constraints several times will not change the result either, so the following rule in the constructed context-free grammar is also effective:

(6.13)

$$\mathrm{F}'{:}v_c{:}\left\{\begin{array}{c}(v_c\ \textsc{pred}){=}\text{‘see}\langle\ \ldots\rangle\text{’}\\ (v_c\ \textsc{tns}){=}\textsc{past}\\ (v_c\ \textsc{subj})=v_{cs}\\ (v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\ (v_c\ \textsc{obj})=v_{co}\\ (v_{co}\ \textsc{pred}){=}\text{‘Titanic’}\\ v_c=v_c\end{array}\right\}$$

$$\to \mathrm{F}{:}v_c{:}\left\{\,(v_c\ \textsc{tns}){=}\textsc{past}\,\right\}\ \mathrm{FP}{:}v_c{:}\left\{\begin{array}{c}(v_c\ \textsc{pred}){=}\text{‘see}\langle\ \ldots\rangle\text{’}\\ (v_c\ \textsc{tns}){=}\textsc{past}\\ (v_c\ \textsc{subj})=v_{cs}\\ (v_{cs}\ \textsc{pred}){=}\text{‘Mary’}\\ (v_c\ \textsc{obj})=v_{co}\\ (v_{co}\ \textsc{pred}){=}\text{‘Titanic’}\\ v_c=v_c\end{array}\right\}$$

In this case, the F^0 category is matched by the lexicon entry for *had*, leading to

(6.14) a. John thought that Mary had had seen Titanic.
b. John thought that Mary had had had seen Titanic.

Other choices in generation arise from the freedom of generating the subject in the specifier of VP or FP and from the possibility of (unbounded) topicalization of the object (rule (6.8a) contains a functional-uncertainty equation). So, we will also get the following generation alternatives:

(6.15) a. John thought that Titanic, Mary had seen.
b. Titanic, John thought that Mary had seen.

Note that some of these indeterminisms are due to insufficient restriction of the sample grammar (e.g., the multiple *that*s or *had*s), others could be argued to be a linguistically justified model of “real” generation alternatives (as in the topicalization case). With classical LFG grammars it seems to be a safe assumption that vacuous recursions, as in the *that* example, are not intended by grammar writers. Hence, the strategy of not passing such cycles (or possibly passing them at most once) is sensible.[9] As we will see in the next subsection, the situation with G_{inviol} in OT-LFG is slightly different.

[9] The “offline generability” condition employed in the XLE system is based on this strategy; cf. fn. 1 on page 160 above.

LFG generation in OT-LFG

We can now also think of candidate generation in OT-LFG as the construction of a context-free grammar producing the set of (terminal strings in the) candidate analyses. This means that the OT constraints have to help us determine the subset of candidates (often just a singleton) that is most harmonic with respect to the given constraint ranking. Note that in this context, it is certainly *not* justified to generally exclude recursive application of the rules. While with classical grammars, the presence of recursions could be assumed to arise from unintended underrestriction of the grammar, the lack of restriction in the G_{inviol} grammar in OT-LFG is absolutely intentional. It is the job of the constraints to add the required restrictions, but G_{inviol} has to ensure that all candidates are generated in the first place. For instance, DEP-IO violations as in *Who did you see* will arise by passing a recursion in the context-free grammar constructed during generation.

As discussed extensively in chapter 4, a candidate containing such a vacuous cycle has still the chance to become the winner of the competition. If the DEP-IO constraint is outranked by some other constraint that is violated by the non-recursive structure but satisfied by the larger, recursive structure, the resulting harmony is increased by going through the recursion a certain number of times. It is for this very reason, that *Who did you see* is predicted to be grammatical in English.

Intuitively, there seems to be an upper limit to the number of useful passes through such a recursion: the best one can do is to avoid all the constraint violations that would have otherwise arisen. Beyond this point, continued application of the recursion will not have any positive effect on harmony. This intuitive interdependence is brought out so clearly thanks to the construction of (Kaplan and Wedekind 2000). In the following section, an extension of their system is presented that establishes the conditions under which this OT-constraint control over candidate generation is formally guaranteed.

6.2.2 OT-LFG generation

The most straightforward approach to the OT-LFG scenario would probably be the following: (i) apply Kaplan and Wedekind's construction on G_{inviol} directly (i.e., given an input f-structure Φ_{in} construct $KW(G_{inviol}, \Phi_{in})$), and (ii) use the resulting context-free grammar to generate candidates and check them for constraint violations. However, it is less straightforward how generation with the context-free grammar can be restricted in a way that avoids eternal expansion of recursions (the "pumping" situation) while at the same time ensuring that all relevant candidates are generated.

The strategy I propose instead is the following: the observations of sec. 4.4.4 – which suggested that a rule-local formulation of OT constraints is sufficient for modelling the linguistic intuitions behind OT syntax – are exploited to convert the LFG grammar G_{inviol} to a different form $O_{\mathcal{C}}(G_{inviol})$ (depending on the constraint set $\mathcal{C}$), which is however still an LFG grammar. Now, when Kaplan and Wedekind's construction is applied to $O_{\mathcal{C}}(G_{inviol})$, all "pumping" structures generated by the context-free grammar $KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})$ can indeed be ignored since all OT-relevant candidates are already contained in the finite set of non-recursive structures – i.e., the structures in which no c-structure tree path from the root symbol to a terminal category contains the same nonterminal symbol more than once. So, as a final step (which is trivial in terms of decidability), the ranking of the constraints is taken into consideration in order to determine the harmony of all the candidates in this finite subset of the full candidate set and thus finally find the optimal candidate.

The conversion $O_{\mathcal{C}}(G_{inviol})$

The extra conversion of the candidate generation grammar G_{inviol} is similar in spirit to the construction that Kaplan and Wedekind apply. The category representation is augmented in order to take more fine-grained distinctions into account. In our case, the relevant distinctions arise from the number of constraint violations incurred locally. I assume that at the level of c-structure, the category representation in G_{inviol} is already fine-grained enough to encode the distinctions checked for in the OT constraints (cf. sec. 4.4.4). So, each OT constraint schema has one of the following implicational forms:

(6.16) a.
$$\begin{array}{c} N \\ S[\star] \end{array} \Rightarrow \begin{array}{c} N' \\ S'[\star] \end{array}$$

where N, N' are descriptions of nonterminal symbols of G_{inviol}; S, S' is a standard LFG f-annotation of constraining equations with $\star$ as the only f-structure metavariable (interpreted as $\phi(N)$).[10]

b.
$$\begin{array}{c} N \\ \overline{\rho \;\; \begin{array}{c} M \\ S \end{array} \;\; \sigma} \end{array} \Rightarrow \begin{array}{c} N' \\ \overline{\rho' \;\; \begin{array}{c} M' \\ S' \end{array} \;\; \sigma'} \end{array}$$

where N, N', M, M' are descriptions of nonterminal symbols of G_{inviol}, N and N' refer to the mother in a local subtree configuration, M and M' refer to the same daughter category; $\rho, \rho', \sigma, \sigma'$ are regular expressions over nonterminals of G_{inviol}; S, S' are standard LFG f-annotations of constraining equations.

[10] More generally, explicit reference to the category-level metavariable ($*$ in classical LFG) should be made, i.e., other projections than ϕ are also permitted.

Recall from sec. 4.4.4 that I assume structured representation for c-structure categories ("complex category symbols"), i.e., the *descriptions* of nonterminal symbols may specify ome properties (e.g., bar level), leaving certain other dimensions (e.g., lexical class) underspecified. As a special case, such descriptions may be entirely underspecified, expressing no restriction on the category. With this special case, (6.16a) covers OT constraints that make reference to f-structure only (although the f-structures that can be referred to need to be "anchored" in a rule or lexicon entry).

Preprocessing Like Kaplan and Wedekind (2000), I assume that the grammar G_{inviol} has undergone an initial preprocessing step in which (i) the c-structure part of rules has been converted into standard context-free form, i.e., the right-hand side is a category string rather than a regular expression.[11] Lexical entries are transformed to standard rule format to (e.g., "V → see", with f-annotations referring to ↑ only). Furthermore (ii), f-structural constraint schemata which contain disjunctions have been transformed in such a way that the disjunctions are propagated to the rule level – leading to alternative rules, each with non-disjunctive f-annotations.

Format conversion (i) ensures that for a given local subtree, each constraint can be applied only a finite number of times: if l is the arity of the longest right-hand side of a rule, the maximal number of local violations is l (since some constraints of type (6.16b) can be instantiated to all daughters). Conversion (ii) ensures that we can keep track of the violation of f-structural constraints at the level of rules.

Grammar conversion With the number of local violations bounded, we can encode all candidate distinctions with respect to constraint violations at the local-subtree level with finite means; in particular, we can augment the category representation in such a way that the number of local violations for all constraints is explicitly represented. The set of categories in the newly constructed LFG grammar $O_{\mathcal{C}}(G_{inviol})$ is the finite set

(6.17) $\mathcal{N}_{O_{\mathcal{C}}(G_{inviol})}$: *the set of categories in* $O_{\mathcal{C}}(G_{inviol})$

$$\begin{array}{ll} \{\, N{:}\langle n^1, n^2, n^3 \ldots n^k\rangle \mid & N \text{ a nonterminal symbol of } G_{inviol}, \\ & k \text{ the size of the constraint set } \mathcal{C}, \\ & 0 \leq n^i \leq l, \\ & l \text{ the arity of the longest rhs in rules of } G_{inviol} \,\} \end{array}$$

[11] In this context, I also assume that the c-structural OT constraints are adjusted to this format, i.e., the conversion of Kleene stars to rule recursions is also reflected in the constraint schemata.

The rules in $O_{\mathcal{C}}(G_{inviol})$ are constructed in such a way that for each rule

$$\begin{array}{llll} \mathrm{X}_0 \rightarrow & \mathrm{X}_1 & \ldots & \mathrm{X}_m \\ & T_1 & & T_m \end{array}$$

in G_{inviol} and each sequence $\langle n_0^1, n_0^2 \ldots n_0^k\rangle$, $0 \leq n_0^i \leq l$, all rules of the form

$$\begin{array}{llll} \mathrm{X}_0{:}\langle n_0^1, n_0^2 \ldots n_0^k\rangle \rightarrow & \mathrm{X}_1{:}\langle n_1^1, n_1^2 \ldots n_1^k\rangle & \ldots & \mathrm{X}_m{:}\langle n_m^1, n_m^2 \ldots n_m^k\rangle\,, \; 0 \leq n_j^i \leq l \\ & T_1' & & T_m' \end{array}$$

are included such that n_0^i is the number of violations of constraint C^i incurred local to the rule (and the f-annotations $T_1' \ldots T_m'$ are appropriately specified), i.e.[12]

(6.18) for C^i of form (6.16a) $\begin{bmatrix} N & \Rightarrow & N' \\ S[\star] & & S'[\star] \end{bmatrix}$:

a. $n_0^i = 0$; $T_j' = T_j$ $(1 \leq j \leq m)$
if X_0 does not match the condition N;

b. $n_0^i = 0$; $T_1' = T_1 \wedge \neg S[\star/\uparrow]$; $T_j' = T_j$ $(2 \leq j \leq m)$
if X_0 matches N;

c. $n_0^i = 0$; $T_1' = T_1 \wedge S[\star/\uparrow] \wedge S'[\star/\uparrow]$; $T_j' = T_j$ $(2 \leq j \leq m)$
if X_0 matches both N and N';

d. $n_0^i = 1$; $T_1' = T_1 \wedge S[\star/\uparrow]$; $T_j' = T_j$ $(2 \leq j \leq m)$
if X_0 matches N but not N';

e. $n_0^i = 1$; $T_1' = T_1 \wedge S[\star/\uparrow] \wedge \neg S'[\star/\uparrow]$; $T_j' = T_j$ $(2 \leq j \leq m)$
if X_0 matches both N and N';

[12] $S[\star/\uparrow]$ is defined as the f-annotation schemata S' resulting from a replacement of $\star$ in S with ↑. The f-annotations that are added in (6.18) refer to the mother node's f-structure. So it is arbitrary which daughter is picked for annotating them (the ↑ will refer to the mother in any of the daughters' f-annotation). Here I use the first daughter throughout.

(6.19) for C^i of form (6.16b) $\left[\begin{array}{ccc} \overset{N}{\overbrace{\rho \;\; M \;\; \sigma}} & \Rightarrow & \overset{N'}{\overbrace{\rho' \;\; M' \;\; \sigma'}} \\ S & & S' \end{array}\right]$:

a. $n_0^i = 0; T_j' = T_j \; (1 \leq j \leq m)$
if X_0 does not match the condition N;

b. $n_0^i = \sum_{j=1}^{m} d_j; \;\; T_j' = \delta(T_j, S, S') \; (1 \leq j \leq m)$,
where

i. $d_j = 0; \;\; \delta(T_j, S, S') = T_j$
if X_j does not match M, or $X_1 \ldots X_{j-1}$ do not match ρ, or $X_{j+1} \ldots X_m$ do not match σ;

ii. $d_j = 0; \;\; \delta(T_j, S, S') = T_j \wedge S \wedge S'$
if X_0 matches both N and N'; X_j matches both M and M'; $X_1 \ldots X_{j-1}$ match ρ and ρ'; $X_{j+1} \ldots X_m$ match σ and σ';

iii. $d_j = 0; \;\; \delta(T_j, S, S') = T_j \wedge \neg S$
if X_0 matches both N and N'; X_j matches both M and M'; $X_1 \ldots X_{j-1}$ match ρ and ρ'; $X_{j+1} \ldots X_m$ match σ and σ';

iv. $d_j = 1; \;\; \delta(T_j, S, S') = T_j \wedge S$
if X_0 matches N, X_j matches M, $X_1 \ldots X_{j-1}$ match ρ, $X_{j+1} \ldots X_m$ match σ, but (at least) one of them does not match the respective description in the consequent (N', M', ρ', σ');

v. $d_j = 1; \;\; \delta(T_j, S, S') = T_j \wedge S \wedge \neg S'$
if X_0 matches both N and N'; X_j matches both M and M'; $X_1 \ldots X_{j-1}$ match ρ and ρ'; $X_{j+1} \ldots X_m$ match σ and σ'.

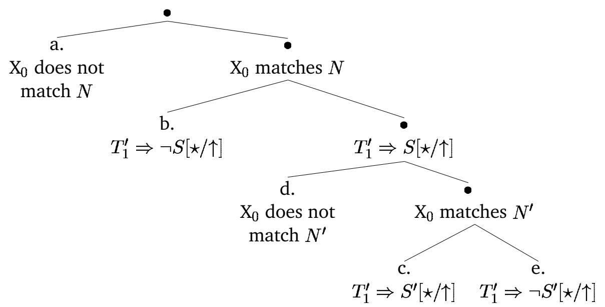
Note that for a particular combination of a rule and a constraint, several new rules can result – even with the exact same number of constraint violations. For instance, if the right-hand side of a rule (X_0) matches both the antecedent (N) and the consequent (N') category description of a constraint of form (6.16a), three clauses apply: (6.18b), (6.18c), and (6.18d). So, we get two new rules with the count of 0 local violations of the relevant constraint and two new rules with count 1. The difference lies in the f-annotations of course. The point of this construction is to make sure that all candidates will still be generated by the modified grammar; the c-structural conflicts can be detected during the construction already, whereas for the f-structural conditions, all options have to be provided in the f-annotations. They will be checked only during generation (or parsing), when a model is constructed from the f-constraints. In some cases, inconsistencies will arise from the newly added annotations, in other cases, different alternative analyses will arise.

Another point to note is that the constraint profile of the daughter categories does not play any role in the determination of constraint violations local to the subtree under consideration (only the sequences n_0^i are restricted by the conditions (6.18) and (6.19); the sequences on the daughter categories n_1^i through n_m^i are unrestricte). This means that for each new rule type, all combinations of constraint profiles on the daughters are constructed. This creates a huge number of rules, but for the present purposes the only relevant aspect is that the number of combinations is finite (since the set of augmented categories is finite). Providing all possible constraint profiles for the daughters ensures that no sentence that can be parsed (or generated) by G_{inviol} is excluded from $O_{\mathcal{C}}(G_{inviol})$ (as stated by fact (6.20)): whichever constraint profiles are constructed for the left-hand side of a G_{inviol} rule by (6.18) and (6.19), it is guaranteed that the respective augmented category can be used in all other rules.

(6.20) *Coverage preseveration*
All strings generated by a (preprocessed) LFG grammar G are also generated by $O_{\mathcal{C}}(G)$.

We have just seen that providing all possible combinations of augmented category symbols on the right-hand rule sides in $O_{\mathcal{C}}(G)$ ensures that the newly constructed rules can be reached from the root symbol in a derivation. What remains to be shown is that for whenever a rule R in G contributes to an analysis, at least one of the rules constructed from R will contribute to the corresponding analysis in $O_{\mathcal{C}}(G)$. This is ensured iff the subclauses in (6.18) and (6.19) cover the full space of logical possibilities. For (6.18) this is easily seen: we get the following case distinction.

(6.21)


a.
X_0 does not match N
X_0 matches N
b.
$T_1' \Rightarrow \neg S[\star/\uparrow]$
$T_1' \Rightarrow S[\star/\uparrow]$
d.
X_0 does not match N'
X_0 matches N'
c.
$T_1' \Rightarrow S'[\star/\uparrow]$
e.
$T_1' \Rightarrow \neg S'[\star/\uparrow]$

Disjoining the alternatives leads to a tautology in all cases, i.e., the disjunction of all new rules expresses no restrictions in addition to those already contained in the original rule. The same holds for (6.19) (note that the cases i.-v. in (6.19) are modelled after a.-e. in (6.18)). This proves fact (6.20).

The original G analysis can be recovered from a $O_{\mathcal{C}}(G)$ analysis by applying a projection function *Cat* to all c-structure categories:

(6.22) *Definition of Cat*
$\mathit{Cat}(N{:}\langle n^1, n^2 \ldots n^k\rangle) = N$ for every category in $\mathcal{N}_{O_{\mathcal{C}}(G_{inviol})}$ (6.17)

We can overload the function name *Cat* with a function applying to the set of analyses produced by an LFG grammar G (which I continue to refer to with the grammar's name by convention) by defining

$\mathit{Cat}(G) = \{\langle T, \Phi\rangle \,|\, \langle T', \Phi\rangle \in G$, T is derived from T' by applying *Cat* to all category symbols $\}$.

Coverage preservation of the $O_{\mathcal{C}}$ construction holds also for the projected c-category skeleton (the same proof applies):

(6.23) *C-structure level coverage preservation*
For a (preprocessed) LFG grammar G: $\mathit{Cat}(O_{\mathcal{C}}(G)) = G$

But the analyses of $O_{\mathcal{C}}(G)$ provide additional information about the OT constraint violations: each category encodes for all the constraints how many violations of them are incurred in the local subtree it dominates. Since the constraint format is assumed to be restricted to locally evaluable constraints, *all* constraints that can be violated by a candidate analysis have to be incurred local to some subtree. Hence the total number of constraint violations incurred by a candidate can be computed by simply summing over all category-encoded local violation profiles:

(6.24) *Total number of constraint violations*
When *Nodes*(T) is the bag (or multiset) of categories occurring in the c-structure tree T, then the total number of violations of constraint C^i incurred by an analysis $\langle T, \Phi\rangle \in O_{\mathcal{C}}(G_{inviol})$ is

$\#_{C^i} = \sum_{N:\langle \ldots n^i \ldots\rangle \in \mathit{Nodes}(T)} n^i$

Define
$\mathit{Total}_{\mathcal{C}}(T) = \langle \#_{C^1}, \#_{C^2}, \ldots \#_{C^k}\rangle$

Applying KW on the new LFG grammar:
OT-LFG Generation Produces Context-free Languages

The grammar $O_{\mathcal{C}}(G_{inviol})$ is a standard LFG grammar, and it generates the same language as G_{inviol}. So, we can apply Kaplan and Wedekind's (2000) construction directly to $O_{\mathcal{C}}(G_{inviol})$. This produces a context-free grammar for a given f-structure Φ_{in} – what I referred to as $KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})$ above. Note that the application of KW fixes the f-structure (which has to be the minimal model for all sets of f-constraints gathered by the context-free grammar), so the f-structural OT constraints – which were only annotated in $O_{\mathcal{C}}(G_{inviol})$ for all logically possible combinations – are now effectively checked. All rule combinations for which the spelled out f-structural constraint clauses lead to an inconsistency are thus filtered out by the KW construction.

After applying both $O_{\mathcal{C}}$ and KW, the category symbols now have the form X:$\langle n^1, \ldots, n^k\rangle{:}v{:}D$, with v and D arising from the KW construction. We can overload the projection function *Cat* again such that $\mathit{Cat}(u{:}v{:}w{:}x) = u$ for all augmented category symbol of the new format and *Cat*(G) is also defined when G is a context-free grammar.

Since the $O_{\mathcal{C}}$ construction preserves the language generated, coverage preservation holds also after the application of KW to $O_{\mathcal{C}}(G_{inviol})$ and G_{inviol}, respectively:

(6.25) $\mathit{Cat}(KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})) = \mathit{Cat}(KW(G_{inviol}, \Phi_{in}))$

But again, the context-free trees are more diverse in the analyses of the $O_{\mathcal{C}}$-based grammar. As pointed out above, they include information about violations of the constraints in $\mathcal{C}$. Since the computation of the total constraint violations (6.24) depends only on the augmented c-structure, it can be performed on the resulting context-free grammar as well. For example, the constraint violation information could be exploited when the context-free grammar is used to generate the actual strings: one could first try to use only rules with no constraint violations, and if that is not successful proceed to rules violating only low-ranked constraints etc.

But the crucial point for our purposes here is the following: when Kaplan and Wedekind's construction is applied on the $O_{\mathcal{C}}$-version of G_{inviol}, all *instances of recursion* in the resulting context-free grammar *create candidates that are at most as harmonic as their non-recursive counterparts*. This follows directly from the fact that all possible constraint violations are encoded in the context-free categories.

Assuming a projection function *CatCount*$(u{:}v{:}w{:}x) = u{:}v$, we can state:

(6.26) If T_1 and T_2 are *CatCount* projections of trees produced by the context-free grammar $KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})$, using exactly the same rules, and T_2 contains a superset of the nodes that T_1 contains, then
$n_1^i \leq n_2^i$, for all n_1^i, n_2^i $(i = 1..k)$ from $\langle n_1^1 \ldots n_1^i \ldots n_1^k \rangle = \mathit{Total}_{\mathcal{C}}(T_1)$, and $\langle n_2^1 \ldots n_2^i \ldots n_2^k \rangle = \mathit{Total}_{\mathcal{C}}(T_2)$.

This fact follows from definition of *Total* (6.24): the violations counts in the additional nodes in T_2 will add to the total of constraint violations (and if none of the additional nodes contains any local constraint violation at all, the total will be the same as in T_1). Intuitively, the effect of the augmentation of the category format is that certain recursions in the pure KW construction (which one may think of as a loop) are unfolded, leading to a longer loop. While the original loop collapsed certain distinctions relevant for the OT constraints, the new loop is sufficiently large to make all relevant distinctions.

This result can be directly exploited in processing: if all non-recursive analyses are generated (of which there are only finitely many) it is guaranteed that a subset of the optimal candidates is among them. If the grammar does not contain any *violation-free* recursion, we even know that we have generated all optimal candidates.

(6.27) A recursion with the derivation path $A \Rightarrow \ldots \Rightarrow A$ is called *violation-free* iff all categories dominated by the upper occurrence of A, but not dominated by the lower occurrence of A have the form $N\langle n^1, n^2 \ldots n^k \rangle$ with $n^i = 0, i = 1..k$

Note that with a violation-free recursion, the set of optimal candidates is infinite, so if the constraint set is set up properly in a linguistic analysis, one would assume that violation-free recursion should not arise. In (Kuhn 2000a) and (Kuhn 2000b; Kuhn 2001b) I assume that the application of such recuresions is excluded in the same way as offline parsability excludes vacuous recursions over a string in parsing. Hence I call this condition the *relaxed offline parsability/generability* condition:

(6.28) *Relaxed offline parsability/generability*
A rule recursion may only be applied if at least one constraint violation is incurred by the recursive structure.

But with Kaplan and Wedekind's (2000) construction, this condition is not necessary for making the generation task with OT-LFG systems solvable. The context-free grammar produced by KW can be transformed further to only generate the optimal candidates according to the constraint ranking $\gg_{\mathcal{L}}$ of the OT system $\mathcal{O} = \langle G_{inviol}, \langle \mathcal{C}, \gg_{\mathcal{L}} \rangle \rangle$, eliminating all but the violation-free recursions in the grammar:

(6.29) *Creating a context-free grammar that produces the optimal candidates*

a. Define
$\mathcal{T}^{NR}_{\Phi_{in}} = \{T \in KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in}) \mid T$ contains no recursion $\}$.
$\mathcal{T}^{NR}_{\Phi_{in}}$ is finite and can be easily computed, by keeping track of the rules already used in an analysis.

b. Redefine $\mathit{Eval}_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}$ to apply on a set of context-free analyses with augmented category symbols with counts of local constraint violations:
$\mathit{Eval}_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(\mathcal{T}) = \{T \in \mathcal{T} | T$ is maximally harmonic in $\mathcal{T}$, under ranking $\gg_{\mathcal{L}}\}$
Using the function *Total* defined in (6.24), it is straightforward to compute for finite sets, i.e., in particular $\mathit{Eval}_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(\mathcal{T}^{NR}_{\Phi_{in}})$.

c. Augment the category format further by one index component.[13] Introduce index $h = 0$ for all categories in $KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})$ of the form X:$\langle n^1, \ldots n^k \rangle$:$v$:$D$, where $n^i = 0$ for $i = 1..k$. Introduce a new unique index $h > 1$ for each node of the form X:$\langle n^1, \ldots n^k \rangle$:$v$:$D$, where $n^i \neq 0$ for some n^i $(1 \leq i \leq k)$ occurring in the analyses $\mathit{Eval}_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(\mathcal{T}^{NR}_{\Phi_{in}})$ (i.e., different occurrences of the same category are distinguished).

d. Construct the context-free grammar
$G^{OT}_{\Phi_{in}} = \langle N^{OT}_{\Phi_{in}}, T^{OT}_{\Phi_{in}}, \mathrm{S}^{OT}_{\Phi_{in}}, R^{OT}_{\Phi_{in}} \rangle$,
where $N^{OT}_{\Phi_{in}}, T^{OT}_{\Phi_{in}}$ are the indexed symbols of step c.;
$\mathrm{S}^{OT}_{\Phi_{in}}$ is a new start symbol;
the rules $R^{OT}_{\Phi_{in}}$ are (i) those rules from $KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})$ which were used in the analyses in $\mathit{Eval}_{\langle \mathcal{C}, \gg_{\mathcal{L}} \rangle}(\mathcal{T}^{NR}_{\Phi_{in}})$ – with the original symbols replaced by the indexed symbols –, (ii) the rules in $KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})$, in which the mother category and all daughter categories are of the form X:$\langle n^1, \ldots n^k \rangle$:$v$:$D$, $n^i = 0$ for $i = 1..k$ (with the new index 0 added), and (iii) one rule $\mathrm{S}^{OT}_{\Phi_{in}} \rightarrow \mathrm{S}_j$:$h$ for each of the indexed versions S_j:h of the start symbols of $KW(O_{\mathcal{C}}(G_{inviol}), \Phi_{in})$.

With the index introduced in step (6.29c), the original recursion in the context-free grammar is eliminated in all but the violation-free cases.

The grammar $\mathit{Cat}(G^{OT}_{\Phi_{in}})$ produces (the c-structure of) the set of optimal candidates for the input Φ_{in}:[14]

[13] The projection function *Cat* is again overloaded to also remove the index on the categories.

[14] Like Kaplan and Wedekind (2000), I made the assumption that the input f-structure in generation is fully specified (i.e., all the candidates have the form $\langle T, \Phi_{in} \rangle$), but the result can be extended to the case where in generation a finite amount of information can be added to

(6.30) $Cat(G^{OT}_{\Phi_{in}}) = \{T \mid \langle T, \Phi_{in} \rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{C}} \rangle}(Gen_{G_{inviol}}(\Phi_{in}))\}$,
i.e., the set of c-structures for the optimal candidates for input f-structure Φ_{in} according to the OT system $\mathcal{O} = \langle G_{inviol}, \langle \mathcal{C}, \gg_{\mathcal{C}} \rangle \rangle$.

To prove fact (6.30) I will show that the c-structure of an arbitrary candidate analysis generated from Φ_{in} with G_{inviol} is contained in $Cat(G^{OT}_{\Phi_{in}})$ iff all other candidates are equally or less harmonic.

Let us take an arbitrary candidate c-structure T generated from Φ_{in} with G_{inviol} such that $T \in Cat(G^{OT}_{\Phi_{in}})$. We have to show that all other candidates T' generated from Φ_{in} are equally or less harmonic than T. Assume there were a T' that is more harmonic than T. Then there must be some constraint $C^i \in \mathcal{C}$, such that T' violates C^i fewer times than T does, and C^i is ranked higher than any other constrain in which T and T' differ. Constraints are restricted in such a way that violations have to be incurred within some local subtree; so T must contain a local violation configuration that T' does not contain, and by the construction (6.18)/(6.19) the $O_{\mathcal{C}}$-augmented analysis of T – call it $O_{\mathcal{C}}(T)$ – must make use of some violation-marked rule not used in $O_{\mathcal{C}}(T')$. Now there are three possibilities:
(i) Both $O_{\mathcal{C}}(T)$ and $O_{\mathcal{C}}(T')$ are free of recursion. Then the fact that $O_{\mathcal{C}}(T')$ avoids the highest-ranking constraint violation excludes T from $Cat(G^{OT}_{\Phi_{in}})$ (by construction step (6.29b)). This gives us a contradiction with our assumption.
(ii) $O_{\mathcal{C}}(T)$ contains a recursion and $O_{\mathcal{C}}(T')$ is free of recursion. If the recursion in $O_{\mathcal{C}}(T)$ is violation-free, then there is an equally harmonic recursion-free candidate T''. But this T'' is also less harmonic than $O_{\mathcal{C}}(T')$, such that it would have been excluded from $Cat(G^{OT}_{\Phi_{in}})$ too. This again means that $O_{\mathcal{C}}(T)$ would also be excluded (for lack of the relevant rules in the non-recursive part). On the other hand, if it were the recursion in $O_{\mathcal{C}}(T)$ that incurred the additional violation (as compared to $O_{\mathcal{C}}(T')$), then there would be a more harmonic recursion-free candidate T'''. However, this T''' would exclude the presence of $O_{\mathcal{C}}(T)$ in $G^{OT}_{\Phi_{in}}$ by construction step (6.29c,d) (only violation-free recursion is possible). So we get another contradiction to the assumption that $T \in Cat(G^{OT}_{\Phi_{in}})$.
(iii) $O_{\mathcal{C}}(T')$ contains a recursion. If this recursion is violation-free, we can pick the equally harmonic candidate avoiding the recursion to be our $O_{\mathcal{C}}(T')$, and we are back to case (i) and (ii). Likewise, if the recursion in $O_{\mathcal{C}}(T')$ does incur some violation, not using the recursion leads to an even more harmonic candidate, for which again cases (i) and (ii) will apply.
Hence, all possible cases lead to a contradiction with the assumptions. So there can be no candidate T' that is more harmonic than our $T \in Cat(G^{OT}_{\Phi_{in}})$.

We still have to prove that if the c-structure T of a candidate analysis generated from Φ_{in} with G_{inviol} is equally or more harmonic than all other candidates, then it is contained in $Cat(G^{OT}_{\Phi_{in}})$. We can construct an augmented version T' of T, such that $Cat(T') = T$ and then show that there is a homomorphism mapping T' to some analysis $T'' \in G^{OT}_{\Phi_{in}}$ with $Cat(T'') = T$.
We can use the constraint marking construction $O_{\mathcal{C}}$ and Kaplan and Wedekind's (2000) construction to construct the tree T' with augmented category symbols of the analysis T. Kaplan and Wedekind's result plus (6.25) guarantee that $Cat(T') = T$. Now, there has to be a homomorphism from the categories in T' to the categories of some analysis in $G^{OT}_{\Phi_{in}}$. $G^{OT}_{\Phi_{in}}$ is also based on $KW(G_{inviol}, \Phi_{in})$ (with an additional index h on each category and some categories and rules of $KW(G_{inviol}, \Phi_{in})$ having no counterpart in $G^{OT}_{\Phi_{in}}$).
Since we know that T is equally or more harmonic than any other candidate generated from Φ_{in}, we know that the augmented tree T' either contains no recursion or only violation-free recursion. If it does contain such violation-free recursions we map all categories N on the recursion paths to the indexed form N:0, and furthermore consider the variant of T' avoiding the recursion(s). For our tree, there is guaranteed to be a counterpart in the finite set of non-recursive trees in $G^{OT}_{\Phi_{in}}$ with all categories pairwise identical apart from the index h in $G^{OT}_{\Phi_{in}}$. We pick this tree and map each of the categories in T' to the h-indexed counterpart. The existence of this homomorphism guarantees that an analysis $T'' \in G^{OT}_{\Phi_{in}}$ exists with $Cat(T'') = Cat(T') = T$. QED

So it could be shown that for OT-LFG systems in which all constraints can be expressed local to a local subtree in c-structure (as discussed in sec. 4.4.4), the generation task from non-cyclic f-structures is solvable. The infinity of the conceptually underlying candidate set does not preclude a computational approach. It is obvious that the construction proposed here has the purpose of bringing out the principled computability, rather than suggesting a particular algorithm for implementation.

6.3 Recognition and parsing for OT-LFG

As discussed in sec. 6.1.2, generation from an input f-structure and the evaluation of the most harmonic candidates solves only one of the tasks associated with a production-based optimization system – what I called (A1) above. For determining whether a given string is contained in the string language of an OT system (the recognition task (A2)) further processing is required.

This circumstance is underlined by the construction in the previous section. The crucial construction step taken over from (Kaplan and Wedekind 2000), which produces the context-free grammar, presupposes a particular underlying f-structure, i.e., a particular input. When we start out with a string, it would be nice if context-free parsing techniques could be applied, but it is not clear

the input f-structure. In this case, the specified routine has to be computed separately for each of the possible f-structural extensions and the result is compared in the end.

what context-free grammar to use since the underlying f-structure is not yet known, so we do not have any context-free KW-grammar yet. Hence, the initial processing step for (A2) has to be more powerful than context-free parsing.

Essentially, we have to apply LFG parsing to determine all possible underlying input f-structures and then perform the (A1) task of ("backward") generation for each of them. In this section we have to ask: is this combined task solvable? I already addressed the problem briefly in sec. 6.1.1: with the possibility of deletion – MAX-IO violations – there is an infinite set of possible underlying f-structures. The offline parsability condition of standard LFG would guarantee that there are only finitely many f-structures for a given string, but according to OT intuitions this condition is too strong.

6.3.1 Undecidability of the unrestricted recognition problem

As the construction in sec. 6.2.2 showed, infinity issues do not generally preclude a computational approach. Generation of infinitely many generation alternatives in the context of (A1) could be controlled since they were standing in competition. The most harmonic candidate according to the constraints had to be found. However, the situation in the (A2) task – parsing with an OT system using production-based optimization to define grammaticality – is different. The different analyses of the input string are real alternatives, without any mutual interdependence (this would be different in a comprehension-based optimization context). So there is almost no exploitable structure in the infinite set of parses for the given string.

Even with the restrictions on the OT-LFG system which guarantee that the generation problem is solvable, we can construct an undecidability argument. Modifying the second construction discussed in sec. 4.2.3 ($\mathcal{O}_2$), we get the following system:[15]

(6.31) *Constructed OT-LFG system (schema) $\mathcal{O}_3$*

Assume an LFG G_1 for which the emptiness problem is undecidable (i.e., it is undecidable whether $\mathcal{L}(G_1) = \emptyset$).

Construct G_1' from G_1 by replacing all occurrences of all terminal symbols in the rules (i.e., typically just the LFG lexicon entries) with the empty string ϵ. Note that $\epsilon \in \mathcal{L}(G_1')$ iff $\exists s$ s.t. $s \in \mathcal{L}(G_1)$. Hence, $\mathcal{L}(G_1') = \emptyset$ is also undecidable.[16]

Now construct G_{inviol} (with start symbol S) from G_1' (with start symbol S_1') by adding new nonterminal symbols Y and B, new terminals *yes* and *better*, and the following productions:

$$\begin{array}{lll} S \rightarrow & Y & S_1' \\ & (\uparrow\text{PRED})=\text{`yes'} & (\uparrow\text{OTHER})=\downarrow \\ S \rightarrow & Y & \\ & (\uparrow\text{PRED})=\text{`yes'} & \\ S \rightarrow & B & \\ & (\uparrow\text{PRED})=\text{`yes'} & \\ Y \rightarrow \textit{yes} & & \\ B \rightarrow \textit{better} & & \end{array}$$

Assume a single constraint (in addition to the faithfulness constraint MAX-IO which is violated whenever the G_1' rules introduce an empty string):

$$C^1(\Phi, \langle T, \Phi' \rangle) = \begin{array}{l} 0 \text{ if } T \text{ contains the symbol B} \\ 1 \text{ otherwise} \end{array}$$

The ranking of C^1 wrt. MAX-IO does not play a role.

Now, what happens when we want to determine whether *yes* $\in \mathcal{L}(\mathcal{O}_3)$? After (incomplete) parsing of the string *yes* with G_{inviol}, we get an analysis with the second S production, giving us the f-structure $\Phi_1 =$[PRED 'yes']. We have to apply backward generation to this underlying form. This gives us the following production-based optimization:

(6.32)

Input F-Structure: [PRED 'yes']	C^1	MAX-IO
a. [$_{\text{Y}}$ *yes*]	*!	
b. ☞ [$_{\text{B}}$ *better*]		

The string *yes* is less harmonic than the alternative candidate *better*. So for the underlying representation Φ_1, the string *yes* is not a grammatical surface form. But this does not exclude that *yes* is grammatical for some other underlying representation. We can still use the first S production in the initial parsing step. The terminal symbol *yes* may be "followed" by an empty string introduced by the S_1' symbol. If this is the case, the f-structure produced for S_1' is introduced under the feature OTHER, so we get a different underlying representation Φ_2 and we have to perform a different backward generation task. So, in this case no alternative candidate satisfying C^1 can be generated (the only way of satisfying C^1 is by using the third S production, which provides no way

[15] This system is again related to Johnson's (1998) sketch of an undecidability argument for OT parsing.

[16] Johnson (1988) shows the undecidability of parsing with a similar grammar by construction of a Turing Machine.

of creating the f-structure material under OTHER). Thus the MAX-IO violations that the candidate(s) incur would play no role and some candidate with the string *yes* would be optimal – this means *yes* $\in \mathcal{L}(\mathcal{O}_3)$. However, in order to determine whether or not an empty string follows the symbol *yes* in the string parsed inititally the emptiness problem for G_1' would have to be solved, which is undecidable by assumption. So it is also undecidable whether *yes* $\in \mathcal{L}(\mathcal{O}_3)$.

However again something about this problem appears to be counterintuitive. G_1' displayed instances of massive ellipsis (the introduction of the empty string ϵ always goes along with a MAX-IO violation). And linguistically, it does not make much sense to reason about such massive ellipsis without taking the utterance context and/or world knowledge into account (recall the discussion in sec. 5.2.2). If such violations are possible in optimal candidates then they are justified by (contextual) recoverability for the hearer. To model this intuition we have to adjust the formal framework to allow for reference to context and restrict the initial parsing step by context.

Another possibility for ensuring decidability of the parsing task is to shift attention from production-based optimization models to a strong bidirectional optimization model. Both approaches are discussed in the following section.

6.3.2 Decidability of variants of the parsing task

Context as a bounding factor for analyses in parsing

In this subsection, I discuss a strategy of ensuring decidability of the recognition/parsing task by building a kind of contextual recoverability condition into the parsing step of task (A2) (with a simple production-based optimization model).

Let us assume a context representation that is input to the parsing process – in addition to the string. Like in sec. 5.3.3, we can assume a set of f-structures as the context representation. The relevant salient context for a given utterance can be safely assumed to be finite. We also need a structurally controlled way in which the contextual contribution is (re-)introduced to the f-structure of the present utterance. Here, the idea of "pseudo-lexical constraints" discussed in sec. 4.6.2 on page 113 can be used. A generalized form of the sample rule (4.80) for introducing such f-annotations at the level of maximal projections is (6.33).

(6.33) *Pseudo-lexical constraint introduction*

$$\text{X} \rightarrow \left\{ \begin{array}{c|c} \text{X} & \dots \\ (\uparrow F)=V & \end{array} \right\}$$

for some category X, feature F and value V.

Using such a rule once goes along with one violation of MAX-IO (as in (4.72) on page 107). Let us assume that rules of this format are the only source of MAX-IO violations.

Decidability of parsing with classical LFG grammar is guaranteed by the offline parsability condition. Essentially, non-branching dominance chains of categories are only produced up to the point where a category would occur for the second time. As discussed in (Kuhn 1999b, 10), this condition is too strict even for classical LFG. In order to cover all linguistically justified cases, usages of the same category name in the grammar rules with different f-annotations have to be distinguished, as formulated in (6.34).[17] This relaxation does not affect decidability.

(6.34) *Revised offline parsability condition*
A c-structure derivation is valid if and only if no category appears twice in a nonbranching dominance chain *with the same f-annotation*.

In the following I show that it is quite natural to combine the revised offline parsability with pseudo-lexical constraint introduction as in (6.33). As long as the pseudo-lexical f-annotations differ, it is now legal to go through a dominance chain with the same category X. Let us assume that (6.33) is restricted by the following contextual condition:

(6.35) In the analysis $\langle T, \Phi \rangle$ of a given utterance, each value V introduced in a pseudo-lexical f-annotation has to correspond to a type-identical f-structural object V' in the set of context f-structures.

For instance, if we introduce ($\uparrow$PRED)='see(x, y)' as a pseudo-lexical f-annotation, there has to be an instance of 'see(x, y)' in the context representation. In the context of *Bill saw Mary*, the analysis for *and John* can thus build on correspondence with the PRED values of *Bill* and *see* in the context representation. Note that semantic forms are treated as instantiated objects, so the two

[17] According to an LFG reviewer (for the LFG '99 conference), this was pointed out already in the early 1980's by Lori Levin, and the revised offline parsability condition is used in LFG systems like XLE.

instances of ‘see(x, y)’ are automatically distinguished by different indices (e.g., ‘see(x, y)’$_{23}$ as V' and ‘see(x, y)’$_{78}$ as the newly introduced value in Φ).

I will change the notation for introducing such instantiated objects in f-annotations. Normally, a neutral notation is used specifying just the *type* of instantiated object. In pseudo-lexical f-annotation, I propose to use the *token* of the corresponding contextual object for specification, e.g., ($\uparrow$PRED)=‘see(x, y)’$_{23}$. This does not affect the further treatment of the f-constraint in the f-structural model construction. Once annotation schema gets instantiated (instantiating $\uparrow$ to a particular f-structure), a fresh instantiated object is created – say ‘see(x, y)’$_{78}$ as above.[18] However, for the c-structure-related book-keeping according to revised offline parsability (6.34), all references to the same contextual token V' are identical. This means that a non-branching chain with two references to the same contextual object are excluded.

However, if the context contains two instances of the same type of object a non-branching dominance chain may arise that contains a pseudo-lexical f-annotation for each one. This is desirable since an analysis of ellipsis should allow *and John* in the context of (6.36) to have an f-structure with two instances of the PRED value ‘think(x, y)’ recovered from the context.

(6.36) I thought that Mary thought that Bill saw Sue

Without further restrictions on the pseudo-lexical f-annotations, it is quite obvious that the sketched analysis of ellipsis overgenerates considerably. So for instance, one analysis of *and John* in the context of (6.36) would presumably have the same f-structure as the same utterance can have in the context (6.37):

(6.37) Mary thought that Bill thought that I saw Sue

However, what is relevant here is that the formal restrictions assumed are liberal enough to provide the space for a more precise formulation of a theory of ellipsis. Then, further restrictions can be formulated within the formalism provided. This seems to be the case for the proposed approach.

[18] For complex f-structures introduced by pseudo-lexical f-annotations (as they are for example required to derive the subject in the example *Bill saw Mary – and John*), I have to assume a new mechanism creating a type-identical copy of the entire structure referred to in the context. Note however that the described technique of introducing new instantiated objects for semantic forms in the pseudo-lexical f-annotations is a special case of this more general copy mechanism.
Alternative solutions for dealing with the embedded f-structures would be (i) to extend the legal format for pseudo-lexical f-annotations allowing for feature paths rather than just a single feature; or (ii) to permit pseudo-lexical f-annotations on categories dominating the empty string.

So, it remains to be shown that decidability of the parsing task is ensured with the new formal restrictions. Since the representation of the salient context is finite, there can only be a finite number of different contextual objects used in pseudo-lexical f-annotations. Furthermore there is a finite number of categories in the grammar. This ensures that there is an upper limit for the length of a legal non-branching dominance chain. Hence, for a given string there is only a finite number of different c-structures; for each c-structure, the number of minimal f-structure models is also finite, like in standard LFG parsing, so we can process the f-structures for each of them separately (applying backward generation according to the construction in sec. 6.2.2).

Controlling the set of parses with OT constraints

An alternative way of controlling the infinite set of parsing analyses transfers the OT technique used to control generation alternatives (sec. 6.2.2) to the parsing situation. Constraint interaction can distinguish between the alternatives and exclude certain cycles that are responsible for producing an infinite number of possibilities. In other words, the problem of undecidability of parsing with a production-based optimization model is resolved by moving to a strong bidirectional optimization model (cf. sec. 5.3.1).

For the OT system $\mathcal{O}_3$ (6.31) constructed to illustrate undecidability of the parsing problem, we would thus get an additional condition on well-formed candidates: they have to be optimal in the parsing direction too (i.e., the most harmonic analysis with the given string). So, we would look at all possible analyses of *yes*. Even not knowing the internals of the part of the grammar “under” S$'_1$, it is easy to see that no analysis can be constructed for *yes* that satisfies constraint C^1 (which demands the B category of *better* to be present) and that all (if any) analyses of *yes* using the production S $\rightarrow$Y S$'_1$ would have to incur at least one MAX-IO violation (unless $\mathcal{L}(G_1)$ contained already the empty string, which we can easily exclude by stipulating addition of an extra symbol before constructing G'_1). Hence, the candidate a. in (6.32) – [$_{\mathrm{Y}}$ *yes*] – must be optimal in the comprehension-based candidate set over the string *yes*. Since the same candidate is unoptimal in the opposite optimization of (6.32), we know that *yes* is not contained in the language defined by the strong bidirectional version of $\mathcal{O}_3$ (i.e., *yes* $\notin \mathcal{L}_{2/strong}(\mathcal{O}_3)$).

In a certain sense, the control strategy based on constraint interaction is closer to the spirit of OT. On the other hand, to a certain degree it assumes that production-based optimization and comprehension-based optimization in syntax are mirror images and in particular that the strong bidirectional optimization approach is correct. But as the discussion in chapter 5 suggested, it is not entirely clear so far whether these assumptions are justified. Here I just present the formal considerations showing that the control strategy of applying a bidirection OT model can effectively avoid the problem of undecidability.

The $O_{\mathcal{C}}$-construction proposed in sec. 6.2.2 converts an LFG grammar into another LFG grammar with distinctions at the level of c-structure that allow for a distinction of all possible combination of local constraint violations according to constraint set $\mathcal{C}$. In combination with Kaplan and Wedekind's (2000) construction this allowed us to generate for an input f-structure all distinct types of production-based candidates that have a chance to become the winner.

The same construction can be applied in comprehension-based optimization. The simplest case is an OT system ignoring context in the constraint evaluation – i.e., without context-sensitive constraints like DiscCoher, assumed in sec. 5.3.3. (Of course such a system suffers from the ambiguity problem pointed out by Hale and Reiss (1998), since almost every string is predicted to have a single, unambiguous interpretation.) We can apply the $O_{\mathcal{C}}$-construction to G_{inviol} including pseudo-lexical f-annotations as in (6.33). So the task is to find for an input string w the set of pairs $\langle T, \Phi\rangle \in G_{inviol}$ that are most harmonic in the set of candidate analyses with that string (i.e., the set $Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(Gen_{G_{inviol}}(w))$).

If we assume a finite inventory of features and values (including the predicates in semantic forms), we get a large but finite set of possible pseudo-lexical f-annotations. So, when the $O_{\mathcal{C}}$-grammar is run with the standard LFG offline parsability condition, we can be sure that for a given string, only a finite number of c-structures is produced; hence, termination is guaranteed. For each c-structure, the f-annotations have to be evaluated in order to exclude analyses leading to inconsistencies or incompleteness/incoherence (this is part of standard LFG parsing). From the remaining candidates, the optimal one(s) can be determined by simply summing over the local violations encoded in the augmented c-structure category symbols.

(6.38) a. Parse string w with $O_{\mathcal{C}}(G_{inviol})$, applying standard LFG parsing (obeying the offline parsability condition):
$\mathcal{A}_1(w) = \{\langle T, \Phi\rangle \in O_{\mathcal{C}}(G_{inviol}) \mid w$ is the terminal string/yield of $T\}$.

b. Pick the set of analyses $\mathcal{A}_{O_{\mathcal{C}}(G_{inviol})}(w)$ from $\mathcal{A}_1(w)$ with maximal $Total_{\mathcal{C}}(T)$ for $\langle T, \Phi\rangle \in \mathcal{A}_1(w)\}$.

The question is: does the $O_{\mathcal{C}}$-construction guarantee for parsing too that all relevant candidates are among the ones produced? We have to show that the constructed set of analyses is identical to the set of optimal candidates according to the definition (recall that we overloaded the function *Cat* appropriately to convert the augmented category symbols in an LFG analysis back to the normal c-structure):

(6.39) $Cat(\mathcal{A}_{O_{\mathcal{C}}(G_{inviol})}(w)) = Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(Gen_{G_{inviol}}(w))$

Contrary to the situation with generation where the assumption of violations in all vacuously recursive parts of the grammar (the "relaxed offline parsability/generability" condition (6.28)) turned out to dispensable, we now have to make such an assumption: recursions in the grammar that can be passed string-vacuously, i.e., creating a non-branching chain have to lead to at least one local constraint violation. The simplest way to guarantee this is to assume an Economy-of-structure constraint *Struc which "counts" the number of categories in an analyses and favours the candidates with fewer categories.

To show $Cat(\mathcal{A}_{O_{\mathcal{C}}(G_{inviol})}(w)) \subseteq Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(Gen_{G_{inviol}}(w))$, assume we have an analysis $\langle T, \Phi\rangle$ in the *Cat* projection of the $O_{\mathcal{C}}$-constructed outcome. We have to show that $\langle T, \Phi\rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(Gen_{G_{inviol}}(w))$. Assume that it were not, then there would have to be a more harmonic competitor $\langle T', \Phi'\rangle$ in $Gen_{G_{inviol}}(w)$. Since all the constraints are locally expressed we can exclude that $\langle T', \Phi'\rangle$ is among the offline parsable candidates in $Gen_{G_{inviol}}(w)$: they are checked directly in $\mathcal{A}_{O_{\mathcal{C}}(G_{inviol})}(w)$. So $\langle T', \Phi'\rangle$ must contain at least one non-branching dominance chain with two occurences of a category X. This string-vacuous recursion must incur a constraint violation along the way (by assumption (6.28)) – say $*C^i$. Since $\langle T', \Phi'\rangle$ is optimal, the non-branching dominance chain must avoid the violation of a higher-ranking constraint (say C^j) incurred by the simpler, competitor $\langle T'', \Phi''\rangle$, which is the same as $\langle T', \Phi'\rangle$, apart from avoiding the recursion contained in $\langle T', \Phi'\rangle$.

The difference wrt. C^j between $\langle T', \Phi'\rangle$ and $\langle T'', \Phi''\rangle$ must lie in the local violations for recursion-causing category X, for else avoiding the cycle would definitely be more harmonic. So effectively the local constraint violation profile of the upper X in $\langle T', \Phi'\rangle$ and the single X in $\langle T'', \Phi''\rangle$ differ. But then the $O_{\mathcal{C}}$-construct will have created different augmented symbols for the two profiles and the longer dominance chain of $\langle T', \Phi'\rangle$ will not have been filtered out in the $O_{\mathcal{C}}$-equivalent ("$O_{\mathcal{C}}(\langle T', \Phi'\rangle)$"). This gives us a contradiction with our assumptions because $O_{\mathcal{C}}(\langle T', \Phi'\rangle)$ would have been more optimal than the original analysis "$O_{\mathcal{C}}(\langle T, \Phi\rangle)$", so the construction (6.38) would not have included the latter in $\mathcal{A}_{O_{\mathcal{C}}(G_{inviol})}(w)$, but $O_{\mathcal{C}}(\langle T', \Phi'\rangle)$.

For the opposite direction, $Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(Gen_{G_{inviol}}(w)) \subseteq Cat(\mathcal{A}_{O_{\mathcal{C}}(G_{inviol})}(w))$, we can take the c-structure T from an arbitrary $\langle T, \Phi\rangle \in Eval_{\langle \mathcal{C}, \gg_{\mathcal{L}}\rangle}(Gen_{G_{inviol}}(w))$ and construct an augmented tree T' from it with $Cat(T') = T$. Then we show that $T' \in \mathcal{A}_{O_{\mathcal{C}}(G_{inviol})}(w)$. For the construction of the augmented c-structure T' from T, we apply all constraints locally at each category in the tree T and construct the violation marks of the augmented category format accordingly (the cases in (6.18) and (6.19) can be applied to local subtrees in just the same way as they are applied to rules – the f-annotations have to be evaluated as a check on the existing f-structure model Φ).[19] Note that $\mathit{Cat}(T') = T$. Now, is $T' \in \mathcal{A}_{O_{\mathcal{C}}(G_{\mathit{inviol}})}(w)$? The augmented categories we constructed are in accordance with the $O_{\mathcal{C}}$-construction and the f-annotations were checked against the f-structure model. There cannot be any double occurrences of the same augmented category in a non-branching chain, because then the initial candidate $\langle T, \Phi \rangle$ would not have been optimal (according to a stronger version of the same argument as in the opposite direction – if there is a cycle in the augmented categories, then there must be at least one cycle in the simpler categories). So we know that T' is the c-structure of a successful LFG analysis of the string w in $O_{\mathcal{C}}(G_{\mathit{inviol}})$ (cf. (6.38a)). Since $\langle T, \Phi \rangle$ is known to be most harmonic in $\mathit{Gen}_{G_{\mathit{inviol}}}(w)$ and all constraints are locally confined, there cannot be any candidate in $\mathcal{A}_1(w)$ with a better total constraint profile than $\langle T', \Phi \rangle$, so $\langle T', \Phi \rangle$ is picked in step (6.38b), and thus $(\mathit{Cat}(T') =) T \in \mathit{Cat}(\mathcal{A}_{O_{\mathcal{C}}(G_{\mathit{inviol}})}(w))$. QED

Since the “simple” processing tasks for the production-based optimization model (generation, i.e., (A1)) and for the comprehension-based model (parsing, i.e., (B1)) could be shown to be computationally solvable, the combined tasks ((A2) and (B2)) in a strong bidirectional model are also solvable. Depending on the input representation, (A1) or (B1) can be performed first, and the second task can be applied on the output (after filtering out the relevant information, i.e., the “input part” of f-structure, or the surface string).

Weaker bidirectional models (cf. sec. 5.3.1 and 5.3.2) cannot exploit this strategy since the interdependence of the two directions of optimization is more sophisticated. In order to ensure decidability of the parsing task for them, an additional recoverability condition of the kind discussed in the previous subsection seems to be required.

Adding context-sensitive constraints in OT-controlled parsing

So far, the OT-based control of infinity of the set of parsing analyses ignored context-sensitive constraints. This means that the ellipsis analysis for utterances like *and John* used as an example throughout this dissertation could not be modelled in the framework, since it would require string-vacuous cycles of the type that is excluded (in the comprehension-based direction it will generally be more harmonic to avoid ellipsis). To make a multiply embedded ellipsis optimal, a context-sensitive constraint like DiscCoher (sec. 5.3.3) has to be assumed, outranking the constraints that punish ellipsis. But the approach proposed here can be transferred to a set-up including a context representation. Here, I will only sketch the idea.

[19] If there are several possibilities we construct all of them and pick the most harmonic one based on the total constraint violations.

We can assume a finite context representation and constraints that are still local to subtrees of depth 1, but which can in addition refer to the context representation. The $O_{\mathcal{C}}$-construction is then extended to depend on a particular context representation. With a fixed context, the local constraint violation profile can be computed for all rules in the grammar, again producing augmented category symbols. So, the resulting grammar can be applied in the same way as before, but the augmented set of categories is even more diverse; hence, the non-branching chains that can be constructed before a category is included twice can become considerably larger, and analyses that would have been excluded before can become winners.

Note that with the context-sensitive version of the bidirectional optimization strategy, it is only the parsing task with respect to a given context that is guaranteed to be decidable. If we are interested in the string language generated by the OT system independent of context, the extended $O_{\mathcal{C}}$-construction does not help. I conjecture that the string recognition problem for a contextually sensitive grammar model is semidecidable for principled reasons.

If the context of a given utterance is unknown, the parsing process has to rely on heuristics for the accomodation of a certain amount of contextual information. But at some point, the process has to stop – even at the risk of wrongly excluding a string that is actually grammatical.

If we look at what is actually being modelled by the theoretical concept of grammaticality – namely acceptability judgements of native speakers –, this semidecidability seems rather plausible. Recall under what circumstances candidates that are heavily unfaithful to Max-IO (like the one in (4.72) on page 107) can turn out to be winners: it is when the context allows ellipsis of large chunks of the underlying (input) form.

Now, looking at the human sentence processor in such a situation is quite revealing: as is well-known, when presented with elliptical utterances out of context, our processor breaks down surprisingly fast – in a certain sense. Sentences are judged unacceptable that would be considered perfect if the context was known. For example,

(6.40) Bill for the doctor’s

is likely to be judged ungrammatical if no appropriate context (like *Has anyone left early today?*) is provided (cf. e.g., Klein 1993 for discussion and further examples).

So, the human sentence processing system displays a behaviour suggesting that something like the type of heuristics we just discussed is at work. Undecidability of the parsing task (for the formal system specified by our – idealized – model of competence grammar) may be unavoidable.

6.4 Chart-based processing of OT syntax

This section discusses a particular algorithmic approach for putting to use the results of the previous section. Standard generation and parsing techniques employing the data structure of a chart are extended to processing of OT-LFG systems, as proposed in (Kuhn 2000b) and discussed in (Kuhn 2000a). Crucially, candidate generation and constraint checking are interleaved.

Restrictions on the form of constraints have already been discussed in sec. 6.2. Here I will use the slightly different formulations of (Kuhn 2000b; Kuhn 2001b). The constraints are used to limit the search space, so we have to be sure that the system contains adequate constraints that will differentiate the candidates arising through rule recursion. This justifies the assumption of the *relaxed offline parsability/generability* condition addressed in sec. 6.2.2 and repeated here (note that this is not really a condition on G_{inviol}, but on the constraint set):

(6.28) *Relaxed offline parsability/generability*
A rule recursion may only be applied if at least one constraint violation is incurred by the recursive structure.

Note that it is quite easy to guarantee for an entire OT system that all candidates satisfy (6.28): a sufficient condition is that the set of constraints include the Economy-of-expression constraint *STRUCT.

As discussed in sec. 6.2.2, the constraints may not be of arbitrary complexity. I assume the following restriction:

(6.41) *Restriction on constraints:*
The structure (c-structure/f-structure) denoted by the constraint condition must be bounded.

Note that this restriction is fully compatible with the recurrent strategy of keeping the individual constraints simple and exploit the explanatory effect of several constraints interacting.

6.4.1 Optimality-theoretic Earley deduction

The basic idea of the interleaved candidate generation/constraint checking approach is to use a standard chart for representing partial structures constructed with G_{inviol}, plus in addition for keeping track of the constraint profile of these partial structures. Tesar (1995) proposes such a dynamic programming or chart-based OT algorithm for generation with regular grammars and context-free “position grammars”. This basic idea is extended to OT-LFG in (Kuhn 2000b), using Earley deduction parsing and generation (following Neumann 1994; Neumann 1998).

The constraint profile of (partial) constituents is stored in the chart edges. Whenever a constraint may or may not apply, both options are entered into the chart. The assumption of relaxed offline parsability/generability (6.28) and the boundedness of constraint conditions (6.41) ensure that recursions not helping to avoid some local constraint violation lead back to an already existing edge.

When an identical edge exists in the chart, the new edge is considered to be blocked as usual in chart parsing/generation – however only if the new edge is equally or less harmonic than the existing one. If it is more harmonic, the new constraint profile is propagated through the chart, which will potentially lead to further options. Due to this online processing of constraints, the algorithm can deal with an infinite candidate set.

Earley deduction for parsing and generation

Since the chart-based algorithm to be developed is to work bidirectionally, using Earley deduction is a natural choice. This paradigm was proposed by (Pereira and Warren 1983) as a parsing algorithm for definite clause grammars, and has been extended to generation by (Shieber 1988; Neumann 1994; Neumann 1998, a.o.). I will follow Neumann's account, which aims for maximal uniformity of parsing and generation, reducing the difference of the two to a mere difference in the information used for indexing the results.

Parsing and generation amounts to deduction of a given goal from a database comprising the grammar rules, using two basic inference rules: *prediction* (or instantiation) and *completion* (or reduction). In parsing, the goal's string is specified, whereas in generation, its underlying representation is specified.

The algorithm[20] uses a set of grammar rules (and lexicon entries) as a static data base, a chart as a dynamic data base (which will ultimately contain the result), and an agenda as a control structure. Items on the agenda and in the chart have the form of definite clauses. We distinguish active and passive items: active items are “looking for” material of a certain category and with certain features, whereas passive items state that certain material has already been found. In both cases, an *index* notes which part of the input (string or underlying form) is or should be covered by the respective category. The chart is partitioned into different *item sets*, according to the different indices.

[20] A sample derivation is given in sec. 6.4.1, for the extended algorithm.

Following Neumann's (1994, 1998) notation, we have:

(6.42) Active item

$\langle h \leftarrow b_0, b_1 \ldots b_n; i; idx \rangle$,
where h is the head (lhs) of a rule; $b_0, b_1 \ldots b_n$ is the (remaining part of the) body (rhs) to be found; $i (0 \geq i \geq n)$ marks the *selected* element to be found next; idx the range of the input covered by the selected element.

(6.43) Passive item

$\langle h; \epsilon; idx \rangle$,
where h is the head (lhs) of a rule; idx the range of the input covered by the head.

Active items come into existence through *prediction*: assume there is a grammar rule A → B C, and we are looking for an A. Then prediction tells us we have to find a B (or a C, depending on the selection strategy), for a certain part of A's index (creating an item $\langle$A $\leftarrow$ B C$; 1; idx' \rangle$). When matching active and passive items are found (in the same item set), *completion* applies, reducing the active item to a passive item (e.g., $\langle$A$; \epsilon; idx \rangle$) or another active item (e.g., $\langle$A $\leftarrow$ C$; 1; idx'' \rangle$) (depending on whether the selected element was the only one that was left or not).[21]

The result of applying an inference rule is always first put on the agenda, to mark that it has yet to be dealt with, checking for further possible rule applications. When an item is taken from the agenda, it is first checked whether the same type of item has been dealt with before (i.e., it is already in the chart and thus *blocked*). If not, it is added to the chart, and the inference rules are applied to it.

The algorithm is initialized by putting an active item looking for the grammar's root symbol on the agenda, indexed with the complete input. It terminates when the agenda is empty; if the initial goal can be generated by the grammar, the chart will contain one or more passive items covering the whole input, with the grammar's root symbol as the category.

For indexing the underlying information in generation, I will essentially use the PRED values in the input f-structure, which are treated as resources, i.e., they can be realized exactly once.[22] To identify them uniquely, the semantic index for a given item will be a list of PRED values with their complete paths.

Note that in a "classical" setting, a restriction of indexing to entities with this resource interpretation would mean a limitation (as discussed in (Shieber 1988)): expletive elements, not contributing to the semantics, could not be captured, nor could phrasal expressions, for which not every part comes with a distinct contribution to the meaning. In the OT setting, phenomena of this kind will generally involve faithfulness violations, i.e., they will be covered by the extension discussed in the next subsection.

Chart-based optimization

Using a chart for storing results of partial OT competitions was first proposed in (Tesar 1995). There, it is applied to regular languages and context-free "position grammars." I show how a similar technique can be incorporated into the Earley deduction algorithm, thus permitting processing of full feature grammars (provided assumptions (6.28) and (6.41) are met). Incorporating optimization in this deduction-based paradigm will allow us to see clearly how it relates to known techniques, thus making potential improvements easier.

Conceptually, the extension is strikingly simple: (i) a record of the constraint profile of the structure constructed so far is added to the representation of (heads of) items; (ii) as completion is applied, the OT constraints are applied, recording the sum of new constraint violations and the constraint profile of the passive item consumed in completion;[23] (iii) when taking a passive item from the agenda, checking for blocking (the existence of an item of the same type in the chart), the constraint profile is taken into account: if the new item is more harmonic, it is not considered to be blocked, but is added to the chart.

The blocking check in (iii) is subjected to a restriction operation,[24] as introduced by (Shieber 1985) to ensure that there is only a finite number of possible types of items in each item set.

The following example (based on OT accounts of inversion and questions (Grimshaw 1997; Ackema and Neeleman 1998)) will clarify the workings of the algorithm. It is taken from (Kuhn 2000b) and thus employs a slightly different representation format than assumed in sec. 6.2. The sample grammar

[21] Lexical access or *scanning* can be seen as a special case of *completion*, where an element from the lexicon is used to match the selection of an active item, rather than using a passive item from the chart.

[22] This is in line with the interpretation of PRED values as instantiated features (Kaplan and Bresnan 1982).

[23] This step will introduce new disjunctions in all cases where a given constraint may or may not apply, in the same way as (6.18) and (6.19) are specified.

[24] In order to ensure correctness, the size of the restricted structure will have to be at least as large as the maximal size of structure denoted by constraint, following assumption (6.41); using the abstraction over all constraints as restriction will guarantee this.

is a small extended X-bar fragment, as specified in (6.44). Categories are assumed to have an internal structure (Bresnan 2001; Kuhn 1999b) encoding lexical class, bar level, the lexical/functional distinction, and whether or not they are topmost within an extended projection (Grimshaw 1991) (i.e., a lexical projection with all its functional projections). For clarity, I will however use abbreviations like VP[+top] for $\langle \textit{verb}, \textit{max}, \textit{lex}, +\textit{top}\rangle$. FP[+/−top] is used for functional projections (all of which will be verbal in this example); XP[+/−top] is underspecified for the lexical/functional distinction.

(6.44)

$$\begin{array}{llll}
\text{a. ROOT} \to & \text{XP}[+\text{top}] & & \\
 & \uparrow=\downarrow & & \\[6pt]
\text{b. FP}[\alpha] \to & (\text{NP}[+\text{top}]) & \text{F}'[\alpha] & \\
 & \{\ (\uparrow\textsc{subj})=\downarrow & \uparrow=\downarrow & \\
 & \ \mid (\uparrow\textsc{df})=\downarrow & & \\
 & \ \ (\uparrow\textsc{obj})=\downarrow\} & & \\[6pt]
\text{c. F}'[\alpha] \to & \text{F}[\alpha] & \text{XP}[-\text{top}] & \\
 & \uparrow=\downarrow & \uparrow=\downarrow & \\[6pt]
\text{d. VP}[\alpha] \to & (\text{NP}[+\text{top}]) & \text{V}'[\alpha] & \\
 & (\uparrow\textsc{subj})=\downarrow & \uparrow=\downarrow & \\[6pt]
\text{e. V}'[\alpha] \to & \text{V}[\alpha] & (\text{NP}[+\text{top}]) & \\
 & \uparrow=\downarrow & (\uparrow\textsc{obj})=\downarrow &
\end{array}$$

The functional annotations follow the annotation principles of (Bresnan 2001), saying for instance that the f-structure of a lexical category's complement is introduced under a complement function like OBJ. Functional projections are identified with lexical projections at the level of f-structure (thus the ↑=↓ for both F[α] and XP[−top] in the F′[α] rule). (6.45) lists the lexicon.

(6.45)

they	NP[+top]	(↑PRED)='they' (↑OP)=−
who	NP[+top]	(↑PRED)='who' (↑OP)=+
see	V[_]	(↑PRED)='see'
do	F[_]	(↑PRED)='do'

Under a faithfulness violation it is possible to skip the lexical contribution, e.g., the PRED introduction by *do*. This way, any of the following sentences can be generated (all with the f-structure in (6.47)):

(6.46) a. [$_{\text{VP}}$ they see who]
b. [$_{\text{FP}}$ they do [$_{\text{VP}}$ see who]]
c. [$_{\text{FP}}$ who do [$_{\text{VP}}$ they see]]
d. [$_{\text{FP}}$ who do [$_{\text{FP}}$ they do [$_{\text{VP}}$ see]]]
e. [$_{\text{FP}}$ do [$_{\text{FP}}$ who do [$_{\text{FP}}$ they do [$_{\text{VP}}$ see]]]
f. . . .

(6.47)

$$\begin{bmatrix} \textsc{pred} & \text{`see}(x,y)\text{'} \\ \textsc{subj} & \begin{bmatrix} \textsc{pred} & \text{`they'} \end{bmatrix} \\ \textsc{obj} & \begin{bmatrix} \textsc{pred} & \text{`who'} \\ \textsc{op} & + \end{bmatrix} \end{bmatrix}$$

The following two constraints (adapted from (Grimshaw 1997)) are at work:

(6.48) OP-SPEC
Every operator ([OP +]) is introduced in the specifier of the topmost projection (Spec–XP[+top]).

(6.49) DEP-IO [or FULL-INT]
All lexical f-specifications are used.

With OP-SPEC outranking DEP-IO in English, the candidates in (6.46) will be evaluated as follows:

(6.50)

Candidates		OP-SPEC	DEP-IO
a.	[$_{\text{VP}}$ they see who]	*!	
b.	[$_{\text{FP}}$ they do [$_{\text{VP}}$ see who]]	*!	*
b. ☞	[$_{\text{FP}}$ who do [$_{\text{VP}}$ they see]]		*
d.	[$_{\text{FP}}$ who do [$_{\text{FP}}$ they do [$_{\text{VP}}$ see]]]		**!
e.	[$_{\text{FP}}$ do [$_{\text{FP}}$ who do [$_{\text{FP}}$ they do [$_{\text{VP}}$ see]]]]	*!	***

The Earley deduction algorithm for generation will proceed as follows. Details of the control strategy are ignored here, focusing on clarity of presentation. Items are written with the following notation:

(6.51) ⟨ HEAD ← REMAINING_BODY; $[n, m]$; *index*; book-keeping ⟩;
REMAINING_BODY (empty for passive items): selected element (leftmost) marked by $\underline{\text{underlining}}$; n, m: number of violations of Op-Spec (6.48) and Dep-IO (6.49); semantic *index* is written as a list of paths.

The book-keeping keeps track of the structure constructed so far; for simplicity, I use the string for this purpose. The string does *not* represent the string covered by the selected element, but the entire derivation history!

Details of the control strategy are ignored for clarity of presentation. The agenda is initialized with item

(6.52) ⟨ ANSWER ← $\underline{\text{ROOT}}$; [0,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨⟩ ⟩

Prediction will apply, based on rule (6.44a), giving rise to the following new item:

(6.53) ⟨ ROOT ← $\underline{\text{XP[+top]}}$; [0,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨⟩ ⟩,

which will trigger a chain of predictions (note that the index in these active items is the selected element's index, i.e., unless an ↑=↓ node is selected, the index changes):

(6.54) ⟨ FP[+top] ← $\underline{\text{NP[+top]}}$ F′[+top]; [0,0]; [SUBJ-PRED-THEY]; ⟨⟩ ⟩

(6.55) ⟨ FP[+top] ← $\underline{\text{NP[+top]}}$ F′[+top]; [0,0]; [OBJ-PRED-WHO]; ⟨⟩ ⟩

(6.56) ⟨ FP[+top] ← $\underline{\text{F′[+top]}}$; [0,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨⟩ ⟩

(6.57) ⟨ F′[+top] ← $\underline{\text{F[+top]}}$ XP[−top]; [0,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨⟩ ⟩

(6.58) ⟨ VP[+top] ← $\underline{\text{NP[+top]}}$ V′[+top]; [0,0]; [SUBJ-PRED-THEY]; ⟨⟩ ⟩

(6.59) ⟨ VP[+top] ← $\underline{\text{V′[+top]}}$; [0,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨⟩ ⟩

(6.60) ⟨ V′[+top] ← $\underline{\text{V[+top]}}$ (NP[+top]); [0,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨⟩ ⟩

Each of (6.54) and (6.58) can undergo scanning with the entry for *they*, leading to reduced items (the index contains the remaining material to be generated by the new selection):

(6.61) ⟨ FP[+top] ← $\underline{\text{F′[+top]}}$; [0,0]; [PRED-SEE, OBJ-PRED-WHO]; ⟨*they*⟩ ⟩

(6.62) ⟨ VP[+top] ← $\underline{\text{V′[+top]}}$; [0,0]; [PRED-SEE, OBJ-PRED-WHO]; ⟨*they*⟩ ⟩

Let us look at (6.62). The following prediction

(6.63) ⟨ V′[+top] ← $\underline{\text{V[+top]}}$ (NP[+top]); [0,0]; [PRED-SEE, OBJ-PRED-WHO]; ⟨*they*⟩ ⟩

can be used to scan *see*, resulting in two options, depending whether or not the optional NP is assumed: another active item

(6.64) ⟨ V′[+top] ← $\underline{\text{NP[+top]}}$; [0,0]; [OBJ-PRED-WHO]; ⟨*they see*⟩ ⟩

or a passive item:

(6.65) ⟨ $\underline{\text{V′[+top]}}$ ← ϵ; [0,0]; [PRED-SEE]; ⟨*they see*⟩ ⟩

When creating a passive item, the structural OT constraints are checked; however, in this case, no violations occur.

(6.64) can be used to scan *who*, leading to another passive item (with a different index). Here, we do have a constraint violation: *who* is marked as an operator, but it is not introduced in the topmost specifier position.

(6.66) ⟨ $\underline{\text{V′[+top]}}$ ← ϵ; [1,0]; [PRED-SEE, OBJ-PRED-WHO]; ⟨*they see who*⟩ ⟩

(6.66) triggers completion of the VP[+top] item (not causing any further constraint violations), which again triggers completion of the initial ANSWER item. So, we have a first candidate to cover the entire input.

(6.67) ⟨ $\underline{\text{VP[+top]}}$ ← ϵ; [1,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨*they see who*⟩ ⟩

(6.68) ⟨ $\underline{\text{ANSWER}}$ ← ϵ; [1,0]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO]; ⟨*they see who*⟩ ⟩

Going back to (6.55), this active item can be used scanning *who*

(6.69) ⟨ FP[+top] ← $\underline{\text{F}'[+\text{top}]}$; [0,0]; [PRED-SEE, SUBJ-PRED-THEY];
⟨*who*⟩ ⟩

predicting

(6.70) ⟨ F′[+top] ← $\underline{\text{F}[+\text{top}]}$ XP[−top]; [0,0]; [PRED-SEE, SUBJ-PRED-THEY];
⟨*who*⟩ ⟩

Here, an interesting case of scanning can occur: there is a lexicon entry of the selected category F[_]: *do*. Its f-annotation (introducing [PRED-DO]) does not match the index. But there is the option of using a lexicon entry unfaithfully, introducing a violation of DEP-IO.[25] Note the unchanged index.

(6.71) ⟨ F′[+top] ← $\underline{\text{XP}[-\text{top}]}$; [0,1]; [PRED-SEE, SUBJ-PRED-THEY]; ⟨*who do*⟩ ⟩

Recall that XP[−top] is either VP[−top] or FP[−top]. The VP option will give us a partial derivation quite similar to the VP[+top] case above ((6.62)-(6.65)). Only, the object cannot be realized in the VP, since its resource path has already been used. So, we get only the following passive item:

(6.72) ⟨ $\underline{\text{VP}[-\text{top}]}$ ← ϵ; [0,0]; [PRED-SEE, SUBJ-PRED-THEY]; ⟨*who do they see*⟩ ⟩

This passive item can be used in completion combined with (6.71), resulting in the following passive items for F′[+top] and FP[+top]:

(6.73) ⟨ $\underline{\text{F}'[+\text{top}]}$ ← ϵ; [0,1]; [PRED-SEE, SUBJ-PRED-THEY]; ⟨*who do they see*⟩ ⟩

(6.74) ⟨ $\underline{\text{FP}[+\text{top}]}$ ← ϵ; [0,1]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO];
⟨*who do they see*⟩ ⟩

This will finally trigger completion of (6.52). Note that there is already a passive ANSWER item with the same index: (6.68). So, classically, we would have a case of blocking. But here, the constraint profile is compared, and it turns out that the new ANSWER item is more harmonic. So we replace the first item by this new one:

[25] Although DEP-IO could be modelled to be checked not until passive items are created, it is natural to keep track of violations along with lexical access.

(6.75) ⟨ $\underline{\text{ANSWER}}$ ← ϵ; [0,1]; [PRED-SEE, SUBJ-PRED-THEY, OBJ-PRED-WHO];
⟨*who do they see*⟩ ⟩

Note that this is exactly the analysis in (6.50c) above. But processing is not yet finished.

The other option for (6.71) was that the selected XP[−top] is an FP[−top]; then, we get the following new active item (a.o.):

(6.76) ⟨ FP[−top] ← $\underline{\text{F}'[-\text{top}]}$; [0,1]; [PRED-SEE, SUBJ-PRED-THEY]; ⟨*who do*⟩ ⟩

This will predict

(6.77) ⟨ F′[−top] ← $\underline{\text{F}[-\text{top}]}$ XP[−top]; [0,1]; [PRED-SEE, SUBJ-PRED-THEY];
⟨*who do*⟩ ⟩

which can combine with another unfaithful use of *do*:

(6.78) ⟨ F′[−top] ← $\underline{\text{XP}[-\text{top}]}$; [0,2]; [PRED-SEE, SUBJ-PRED-THEY]; ⟨*who do do*⟩ ⟩

Again, we have a choice for XP[−top]. We can pick VP[−top] again, being able to reuse (6.72). Completion gives us

(6.79) ⟨ $\underline{\text{F}'[-\text{top}]}$ ← ϵ; [0,2]; [PRED-SEE, SUBJ-PRED-THEY]; ⟨*who do do they see*⟩ ⟩

which completes (6.76) and ultimately (6.71):

(6.80) ⟨ $\underline{\text{F}'[+\text{top}]}$ ← ϵ; [0,2]; [PRED-SEE, SUBJ-PRED-THEY]; ⟨*who do do they see*⟩ ⟩

But note that such an item exists already: (6.73). Comparing the constraint profiles, the new option is less harmonic (the existing item used only one *do*: [0,1]).

Further predictions with XP[−top] as FP[−top] are blocked (as in classical chart parsing/generation).

The illustration shows how an infinite set of candidates (basically *who do* do^{+} *they see*) is discarded as an equivalence class at least as bad as one representative. This makes OT processing with an infinite candidate set possible.

The example was simple, but the technique carries over to all constraints satisfying assumption (6.41). It may be required to "pass" a cycle several times before strict harmony decrease (guaranteed by (6.28)) takes effect. The passes of this cyclic structure have the effect of avoiding the violation of some high-ranked constraint.[26] With the constraint size bounded, this construction is guaranteed to terminate. Additional cycle passes will again cause deterioration.

For termination considerations, the ranking of the constraints plays no role, since the deterioration of the constraint profile caused by subsequent passes of a cyclic structure leads to the following situation after a finite number of steps: all larger candidates are less harmonic than an existing candidate A under *any* ranking of the constraints. This situation arises when the larger candidates have the same constraint violations as A, but also some additional violation(s). A is then said to *harmonically bound* the larger candidates (Prince and Smolensky 1993, sec. 9.1.1).

With a finite constraint set and constraint conditions of a bounded size, the number of distinct chart items that have to be constructed in the worst case is also finite. The maximal set of chart items before hitting a blocking situation is the following: for each subset of the input information (i.e., a finite set of feature path combinations), chart items of any possible category, overlaid with all possible combinations of constraint conditions. (The obvious danger of a combinatorial explosion of the search space is irrelevant for these general decidability considerations; some potential starting points for optimizations in the algorithmic sense will be mentioned briefly in sec. 6.4.3.)

6.4.2 Interleaving parsing and generation

As discussed in sec. 6.1.2, the recognition and parsing task (A2) for an OT system involves parsing and backward generation. So far, we have only looked at the generation task (A1), showing that in a chart-based approach candidate generation and constraint checking can be interleaved, so there does not have to be an *a priori* limit to the degree of unfaithfulness in the candidates. Quite obviously, if chart-based parsing is performed in an analogous way, we can implement task (B1). But for task (A2), the OT generation task (A1) has to be combined with an initial parsing task, determining potential underlying f-structures.

Following ideas of (Neumann 1998), this parsing and "backward generation" can be realized in an interleaved way, assuming a double index for passive items, so they can be used in both directions:

The agenda is initialized by an active parsing item, indexed by the entire input string. At the point where normally a passive item i_p is added to the chart, an active generation item is put on the agenda, with the semantic index constructed for i_p in parsing. This will trigger an intermediate generation phase, exploring alternative analyses. Here, optimization applies, leading to an optimal item i_g for the semantic index under consideration. When the generation phase is finished, i_g is compared to i_p. If it is identical, i_p is actually added to the chart; if not, it is ungrammatical and will be discarded (more precisely, a record is kept that this particular item has been shown to be ungrammatical). Later generation phases can use intermediate results of the earlier ones.

[26] Note that an edge avoiding the high-ranked constraint will have been constructed already before hitting the recursion, anticipating the larger structure required. Thus, the violations incurred by the cycle will not cut this branch.

6.4.3 Discussion

The chart-based optimization approach has been implemented experimentally in Prolog. Varges (1997) provides a simple experimental Prolog implementation of the uniform agenda-driven tabular algorithm of Neumann (1998). On this basis, I wrote an experimental implementation of the algorithm illustrated in sec. 6.4.1, and the interleaving discussed in sec. 6.4.2. For this, I extended Varges' set-up to accomodate for LFG-style grammars. In particular, I modified the semantic indexing to capture resource accounting. The parser/generator was tested with small grammars modelling fragments as discussed in the theoretical OT literature (Grimshaw 1997; Bresnan 2000).

There are several obvious sources for exponential behaviour (which is not surprising, since parsing for the base grammars is already worst-case exponential): (i) using more constraints will lead to highly disjunctive structures; (ii) for generation, the number of item sets may grow exponentially in the size of the input f-structure. (ii) is a theoretical option even for non-OT generation (Kay 1996), but the wide-spread unfaithfulness brings it out in the OT case.

For (i), sophisticated techniques from feature grammar parsing (disjunctive lazy copy links) may help, exploiting *de facto* independence of structures in most cases (cf. e.g., Maxwell and Kaplan 1998; Dymetman 1997). Locality restrictions discussed by (Kuhn 2001a) may help to limit problem (ii). Also, exploiting precomputed implications of the constraint ranking should have a considerable effect.

Having couched computational OT syntax in the well-studied paradigm of Earley Deduction will hopefully facilitate such extensions and improvements. Furthermore, the results of research into OT as a grammar theoretical approach are also of interest for the more engineering-oriented applications of OT-style ranking systems, as proposed in (Frank et al. 2001) for instance. Here, the overall system is hybrid with a very dominant "classical", i.e. non-OT, part and a rather limited OT-style extension. The latter has been mainly used as a preference mechnism to decide between alternative parses, and to some extent also in generation. An understanding of the complexity induced by a bidirectional approach and of possible ways of restricting the expressiveness of an OT system will facilitate a more effective (and maybe more efficient) application of the OT-style part in a hybrid system.

6.5 Summary

The main results of this chapter are the following: there are two main issues in the computational processing of OT systems for syntax, the infinity of the candidates set and the directionality issue – i.e., the fact that the recognition task for production-based OT systems involves processing in the opposite direction. Based on computational results for generation with classical LFG grammars (in particular Kaplan and Wedekind 2000) I showed that for a suitably restricted OT-LFG system the generation problem is solvable. The restrictions – locally expressed constraints and full specification of the semantic part of f-structures – are in the spirit of the underlying assumptions of OT, as discussed in the previous chapters.

The recognition/parsing task is undecidable for a production-based OT system allowing arbitrary faithfulness violations. However, there are two plausible ways of constraining the system: a recoverability condition on ellided material based on a finite context representation, or the move to a strong bidirectional optimization model. I showed decidability of the parsing problem for both these constrained systems. If in the bidirectional model context-sensitive constraints are assumed, decidability can be guaranteed only based on a known context representation. Allowing for free accomodation of context with an isolated sentence again leads to an undecidable recognition task. This fact seems cognitively plausible given that native speakers have trouble with grammaticality judgements for non-trivial cases of ellipsis in isolation.

Finally, I sketched a chart-based algorithmic account for putting the computational results of this chapter to use.

Chapter 7

Conclusion

In this dissertation, I proposed a formal framework for making explicit a number of different OT models for syntax. I discussed the intuitions behind the OT assumptions, identifying the requirements for a faithful rendering in the formal apparatus for syntax. Taking into account learnability considerations and following previous work on OT-LFG, I construed the candidates for OT syntax as non-derivational analyses of an underlying LFG-style grammar, where all members of a candidate are invariant in terms of the interpreted part of f-structure. Constraints can be formalized as simple schemata in a structural description language.

The LFG-based formalization provides a tool for investigations of the intricate interrelations that arise (i) when the dual of standard production-based optimization is assumed: comprehension-based (or interpretive) optimization; and (ii) when moreover the two optimization concepts are combined to form a bidirectional model. I discussed ways of isolating syntactic effects from the role that encyclopaedic knowledge and other non-syntactic sources play in disambiguation. The explanatory limitations of the straightforward strong bidirectional model were addressed, and I demonstrated that a weak bidirectional model working with a fixed context representation across candidates can lead to a simplification and clarification of the constraint set.

Finally, the computational properties of the formal models of OT syntax were discussed, identifying the possibility of arbitrary faithfulness violations and the directionality of processing as the two main challenges. The investigation of computational properties adds interesting ways of differentiating between set-ups of OT systems, in particular with respect to the bidirectionality question. Decidability of a model with constraint-controlled faithfulness is guaranteed for a strong bidirectional model, but not for a general unidirectional or weak bidirectional model. Processing relative to a fixed context representation is decidable for the weaker models too.

Based on the OT-LFG formalization, it is easy to specify slightly simplified OT systems for syntax, using a standard parsing/generation system for LFG, like the XLE system. Such an approach takes some of the theoretically assumed power of constraint interaction away (making *Gen* somewhat overrestrictive), but for the purpose of developing and assessing a focused empirical OT account, it should practically always be sufficient. In any event, the manipulation of candidates and constraint sets with a computer is faster and less error-prone than the paper-based construction of tableaux (for which the number of candidates that can actually be worked out is considerably smaller than the candidate sets one may run through the computer).

Outlook

As discussed initially in chapter 1, one of the motivations for the enterprise of formalizing OT syntax was the prospect of a linguistic theory with a precisely defined learning scheme that one can apply on realistic empirical data. With the stochastic constraint ranking of Boersma (1998) or a similar account, the OT learning model can in particular take into account the frequency of linguistic phenomena and lexical items in the training data.

As the discussion of bidirectionality in chapter 5 showed, some aspects of the formal models still need clarification, before one can expect learning simulations on real syntactic data to be directly revealing about the syntactic constraint sets under consideration in theoretical syntactic work. The fixed-context approach seems quite promising however. It could be combined with a non-OT probabilistic estimation of the distribution of context factors.

Within the existing formal framework, there are various points that should be addressed by future research. For instance, what constraints should one assume for modelling native speakers' idiosyncratic knowledge, i.e., knowledge about collocational preferences of lexical items etc. (cf. the brief discussion in sec. 4.3.2)? Moreover, a broad range of syntactic phenomena has to be addressed under the OT perspective; with the context awareness of the weak bidirectional model (sec. 5.3.3), notorious phenomena for broad-coverage grammars like ellipsis and coordination may await a satisfactory analysis that could be validated on corpus data.

One may hope that the theoretically informed bidirectional OT model with its detailed syntactic representations will ultimately improve the results of genuine computational-linguistic tasks like broad-coverage parsing. In the last decade, statistical models have been used and developed to permit corpus-based training of parsers. Recently, also rich syntactic representations have been applied in such models, in particular in the LFG-based accounts of Johnson, Geman, Canon, Chi, and Riezler 1999; Riezler, Prescher, Kuhn, and Johnson 2000. There is an interesting parallel between the log-linear models used in the training of these probabilistic LFG grammars and the OT architecture. As (Johnson 1998) points out, the comprehension-directed variant of the standard OT model[1] can be viewed as a special case of the log-linear model. The ranked violable constraints of OT (counting instances of a certain configuration in the candidate representations) are the correspondents of the “features” for which a log-linear model provides estimated parameters (these “features” or properties are also functions from configurations to numbers).

This formal parallel at the same time reveals a difference in the typical application of the models. In OT, the original motivation comes from production-based optimization (as a definition of grammaticality), while in statistical natural language processing, so far only the comprehension-based, i.e., parsing direction has been explored and used for disambiguation. The work using rich syntactic representations like LFG structures has either relied on existing classical grammars, which were manually written, or on corpora with a detailed syntactic annotation.

The bidirectional OT approach could attempt to take the scope of corpus-based learning with deep linguistic representations considerably further: both the grammaticality-defining constraint ranking and the disambiguation preferences would be learned from training data. The training data would not have to be annotated with the full syntactic target representations of the grammatical framework adopted, but only with a suitable underlying predicate-argument representation (and using bootstrapping techniques, it may be possible to keep the amount of training data required manageable).

[1] Assuming a fixed limit for the number of multiple violations that can be incurred for the constraints.

Summary in German – Zusammenfassung

Formale und komputationelle Aspekte der Optimalitätstheoretischen Syntax

1 Einleitung

Diese Arbeit beschäftigt sich mit den Eigenschaften von Optimalitätstheoretischen (OT-)Grammatikmodellen, vor allem bei der Anwendung auf syntaktische Fragestellungen. Der OT-Ansatz wurde Anfang der 90er Jahre in der Phonologie eingeführt (Prince and Smolensky 1993) (vgl. (Kager 1999) für eine Einführung) und fand dort rasch weite Verbreitung. Auch in der theoretischen Syntax wird das OT-Modell vielfach eingesetzt; eine frühe, sehr einflussreiche Arbeit ist hier (Grimshaw 1997).[2] Der OT-Ansatz ist mit verschiedenen zugrundeliegenden Grammatikformalismen kompatibel. Für die vorliegende Arbeit sind vor allem die Beiträge relevant, die auf der Lexikalisch-Funktionalen Grammatik (LFG) aufbauen und den von Bresnan (1996, 1999, 2000) initiierten Ansatz der OT-LFG bilden; in diesem Rahmen lassen sich die Eigenschaften des OT-Modells unter Rückgriff auf formale und komputationelle Literatur zu unifikationsbasierten Grammatikformalismen beleuchten.

Die Grundidee der OT ist es, Variation zwischen den Sprachen der Welt aus der Interaktion von universellen Beschränkungen (*Constraints*) abzuleiten. Solche Beschränkungen besagen etwa “realisiere skopustragende Elemente (wie Fragewörter) so, dass der Skopus sichtbar markiert wird” oder “vermeide es, Argumente außerhalb ihrer Grundposition zu realisieren”. Die Beschränkungen sind verletzbar und stehen vielfach in einem gegenseitigem Konflikt, der je nach Priorisierung der Beschränkungen unterschiedlich aufgelöst wird

[2] Manuskript-Versionen dieses Artikels gehen zurück bis 1993.

(vgl. [*die Frage*] *wen Anna sah* und [*die Frage*] *Anna wen sah*). Aus dieser Priorisierung, ausgedrückt durch eine Dominanzrelation (*Ranking*) zwischen den Beschränkungen, ergibt sich die typologische Unterscheidung von Einzelsprachen. Als grammatisch wird im OT-Modell diejenige Analyse aus einer Menge von Kandidaten definiert, die am harmonischsten ist, weil sie die unbedeutendsten Beschränkungsverletzungen aufweist. Das Lernen einer bestimmten Sprache reduziert sich damit auf die Bestimmung der sprachspezifischen Beschränkungshierarchie.

OT verbindet den formal-exakten Ansatz der Generativen Grammatik und dessen detaillierte Repräsentationen mit einem datengesteuerten Lernansatz, der es in seiner stochastischen Ausprägung (Boersma 1998) insbesondere erlaubt, Frequenzeffekte abzuleiten. Damit eröffnet sich ein Lösungsweg für ein zentrales Problem der syntaktischen Theoriebildung und besonders des computerlinguistischen Ansatzes, der von den Ergebnissen der Theorie zu profitieren versucht: bislang stieß in der Grammatikentwicklung die Erweiterung von phänomenspezifischen Einzelanalysen auf eine breite Datenbasis typischerweise an eine Grenze, jenseits derer die urspünglichen Generalisierungen eingeschränkt bzw. in feine Fallunterscheidungen aufgeteilt werden mussten, um der erweiterten Datenlage gerecht zu werden. Der OT-Ansatz mit verletzbaren Beschränkungen und einem empirisch basierten Lernverfahren kann möglicherweise ein fein adjustiertes System von Beschränkungsinteraktion entstehen lassen, das einen vergleichbaren Abdeckungseffekt hat wie ein komplexes Fallunterscheidungssystem. Die linguistische Arbeit bewegt sich dabei aber weiterhin auf der Ebene der uneingeschränkten Generalisierungen, und die datenorientierte Feinanpassung geschieht durch Lernverfahren unter Berücksichtigung der Frequenz von Phänomenen und lexikalischen Elementen in den beobachteten Daten.

Bevor ein derartiges Vorgehen zum Einsatz kommen kann, sind eine Vielzahl von Fragen zum Repräsentationsformalismus und zu den Mechanismen des Verarbeitungsmodells zu klären. Die vorliegende Arbeit versucht hier einen Beitrag zu leisten, indem ein nicht-derivationelles formales Modell für die OT-Syntax vorgeschlagen wird und wichtige empirische, formale und komputationelle Eigenschaften diskutiert werden. Die Arbeit gliedert sich in sieben Kapitel. Diese Zusammenfassung folgt dieser Gliederung.

2 Grundlagen der OT

Zum bereits eingangs erwähnten Mechanismus der Beschränkungsinteraktion muss ergänzt werden, wie die miteinander in Wettbewerb stehenden Kandidatenanalysen bestimmt werden. Hierfür wird eine zugrundeliegende bedeutungsnahe Repräsentation angenommen, der *Input*. Eine Funktion *Gen* spezifiziert zu einem gegebenen Input die Kandidatenmenge, wobei Kandidaten generell in ihren Eigenschaften vom Input abweichen können. In *Gen* sind gewisse unverletzbare Prinzipien kodiert, für die Syntax beispielsweise X-bar-Prinzipien. Für jeden Kandidaten werden dann die Beschränkungen überprüft, und die sich ergebenden Verletzungen werden in einem abschließenden Harmonie-Evaluierungsschritt (*Eval*) zur Bestimmung des optimalen Kandidaten herangezogen.

Ein derartiger Wettbewerb wird in der Tableau-Notation folgendermaßen wiedergegeben (hier ein einfaches Beispiel aus der Phonologie, vgl. Kager 1999, sec. 1.7):

(8.1)

Input: /pãn/	*V$_{\text{NASAL}}$	*V$_{\text{ORAL}}$N	ID-IO(nasal)
a. [pãn]	*!		
b. ☞ [pan]		*	*

Links oben wird der zugrundeliegende Input notiert, hier eine Kette von zugrundeliegenden Lautsegmenten, wie sie im Lexikon angenommen würde. (In der Syntax wird als Input eine erweiterte Prädikat-Argument-Struktur angenommen.) In der linken Spalte werden die möglichen Kandidaten – im Beispiel phonetische Realisierungen: [pãn] und [pan] – aufgelistet (hier sind nur zwei gezeigt, obgleich die Menge im Prinzip unendlich ist). In den weiteren Spalten sind die Beschränkungen notiert, hier drei: *V$_{\text{NASAL}}$, *V$_{\text{ORAL}}$N und ID-IO(nasal). Üblicherweise werden die Beschränkungen von links nach rechts in der Ordnung der sprachspezifischen Hierarchie aufgelistet. Explizit heißt das: *V$_{\text{NASAL}}$ ≫ *V$_{\text{ORAL}}$N ≫ ID-IO(nasal). Die hier verwendeten Beschränkungen sind folgendermaßen definiert:

(8.2) a. *V$_{\text{NASAL}}$
Vokale dürfen nicht nasal sein.

b. *V$_{\text{ORAL}}$N
Vor einem tautosyllabischen Nasal dürfen Vokale nicht oral sein.

c. IDENT-IO(nasal)
Die Spezifikation des Merkmals [nasal] bei einem Input-Segment muss in seinem Output-Korrespondenten erhalten sein.

(8.2a) und (8.2b) werden als Markiertheitsbeschränkungen bezeichnet. Sie nehmen nur auf die Struktur des Kandidaten Bezug. Der gegenseitige Konflikt ist hier offensichtlich. (8.2c) ist eine Treuebeschränkung, die das Verhältnis der Kandidatenstruktur zum zugrundeliegenden Input beurteilt.

Für jeden der beiden Kandidaten in (8.1) sind die Verletzungen dieser Beschränkungen durch einen Stern in der entsprechenden Spalte notiert. Da Kandidat (8.1a) einen nasalen Vokal enthält, verletzt er $*V_{\text{NASAL}}$; Kandidat (8.1b) verletzt dagegen durch die Sequenz [an] $*V_{\text{ORAL}}N$ und weiterhin IDENT-IO(nasal), da die Nasalität nicht getreu der zugrundeliegenden Form realisiert ist. Unter der gegebenen Beschränkungshierarchie ist Kandidat (8.1b) der harmonischste. Dies ergibt sich durch direkten Vergleich der Verletzungen (jeweils paarweise für zwei Kandidaten, auch wenn der Wettbewerb größer ist): Für die am höchsten rankierte Beschränkung, in der sich beide Verletzungsprofile unterscheiden, hat (8.1b) weniger Verletzungen. Beim unterlegenen Kandidaten wird durch ein Ausrufezeichen signalisiert, dass weitere Verletzungen keine Rolle mehr spielen. Der Kandidat, der zuletzt übrig bleibt, wird als Gewinner mit dem Symbol ‘☞’ markiert. Wie im Beispiel zu sehen ist, kann durchaus ein Kandidat mit mehreren Verletzungen optimal sein, wenn er die Verletzung einer hoch rankierten Beschränkung vermeiden kann.

Eines der wesentlichen Erklärungsmittel in der OT ist die faktorielle Typologie. Darunter wird der Raum der als möglich vorhergesagten Sprachen verstanden, die sich aus einer Umordnung der Beschränkungen ergeben. Wird zum Beispiel $*V_{\text{NASAL}}$ tiefer rankiert, dann geht Kandidat (8.1a) als Gewinner gegenüber (8.1b) hervor. Bei den drei Beschränkungen gibt es insgesamt sechs Ordnungsvarianten, die nur vier empirisch zu unterscheidende Sprachsysteme vorhersagen. Solche Vorhersagen lassen sich bei einem OT-System also unmittelbar anhand von typologischen Daten zu den Sprachen der Welt empirisch überprüfen. In Kapitel 2 werden anhand der formalen Eigenschaften der OT-Typologie einige Kriterien diskutiert, die an sinnvolle Beschränkungsmengen gestellt werden können.

3 Beobachtungen zur OT-Syntax

Will man das OT-Modell auf syntaktische Phänomene anwenden, so stellen sich einige Fragen zur Mächtigkeit und anderen Eigenschaften des Formalismus. Dies gilt insbesondere dann, wenn man davon ausgeht, dass es Teil des OT-Programms ist, möglichst alle Aspekte der Variation zwischen Sprachen als einen Effekt der Beschränkungsinteraktion abzuleiten. In dieser Arbeit wird dies als methodologisches Prinzip der OT angenommen.

Was die benötigte Mächtigkeit des Formalismus angeht, sind besonders solche Phänomene aussagekräftig, die auf die Verletzung von Treuebeschränkungen hindeuten. Sie bestimmen, Kandidaten welcher Art von *Gen* erzeugt werden müssen. Die stärksten Abweichungen ergeben sich durch Verletzungen der folgenden beiden Treuebeschränkungstypen:

(8.3) a. DEP-IO: Output-Segmente müssen Input-Korrespondenten haben. – ‘Keine Epenthese’

b. MAX-IO: Input-Segmente müssen Output-Korrespondenten haben. – ‘Keine Löschung’

Das Standardbeispiel aus der Phonologie zur Motivation dieser Beschränkungen ist die Silbenstruktur: in Sprachen, die eine einfache Silbenstruktur fordern (durch hochrankierte Markiertheitsbeschränkungen), veranlassen Inputs, die dieser Struktur nicht genügen, dass auf der Oberfläche epenthetische Segmente eingefügt werden, bzw. dass zugrundeliegende Segmente gelöscht werden. Die Entsprechung im Bereich Syntax sind expletive Elemente wie das *do*-Auxiliar im Englischen (8.4) und unrealisierte Argumente wie das Null-Subjekt im Italienischen (8.5). Der Vergleich mit anderen Sprachen (wie hier dem Deutschen) zeigt jeweils, dass eine Erklärung aufgrund von Beschränkungsinteraktion erforderlich ist.

(8.4) *Das expletive ‘do’ im Englischen*

a. Who did John see

b. Wen sah John

(8.5) *Unrealisiertes Pronomen im Italienischen*

a. Er hat gesungen

b. _ ha cantato
hat gesungen

Sollen derartige Effekte in der Syntax ausschließlich und in einer allgemeinen Art und Weise aus der Beschränkungsinteraktion hergeleitet werden, müssen durch *Gen* beliebig stark vom Input abweichende Kandidaten erzeugt werden.

Des weiteren werden in Kapitel 3 Aspekte der Lernbarkeit diskutiert. Das Lernproblem stellt sich in OT als die Aufgabe dar, aufgrund von Lerndaten die korrekte Ordnung über die Beschränkungen abzuleiten. Sowohl der *Constraint-Demotion*-Algorithmus (Tesar 1995; Tesar and Smolensky 1998), als auch der auf einer stochastisch modifizierten Beschränkungshierarchie basierende *Gradual-Learning*-Algorithmus (Boersma 1998) arbeiten mit fehlergesteuerten Lernschritten. Dazu muss vom Lerner eine falsche Vorhersage seines bisher angenommenen Systems identifiziert werden, d.h. es wird erkannt, dass eine andere als die beobachtete Struktur als Gewinner erwartet würde. Dies setzt voraus, dass der Lerner Rückschlüsse über den zugrundeliegenden Input ziehen kann. Diese Möglichkeit fehlt in einem OT-System, in dem die *Interpretation* der Kandidaten vom zugrundeliegenden Input abweichen kann – eine Annahme, die von Legendre, Smolensky, and Wilson (1998) zur Ableitung von sprachspezifischer Unaussprechbarkeit (*Ineffability*) gemacht wird (vgl. die bidirektionale Optimierung in Kapitel 5 als Alternative).

Abschließend werden der nicht-derivationelle Charakter sowohl des Optimierungssystems als auch der zu vergleichenden Kandidatenanalysen als vorteilhafte Eigenschaften des formalen Systems konstatiert. Der Input ist somit nicht als Eingabe in einem tatsächlichen Prozess zu sehen. Seine Funktion reduziert sich auf die Definition der konkurrierenden Kandidaten.

4 Formalisierung der OT-Syntax im Rahmen von LFG

Als ein Kernbeitrag dieser Arbeit wird eine Formalisierung des OT-Modells auf der Grundlage des LFG-Formalismus vorgestellt. Insbesondere werden Entscheidungsspielräume bei der Umsetzung der intuitiven Konzepte im formalen Modell diskutiert. (Die Grundbegriffe des LFG-Formalismus werden in Abschnitt 4.1 dargestellt; wesentlich ist das System der parallelen Repräsentationsebenen von C-Struktur und F-Struktur, die durch die Abbildungsfunktion ϕ in Korrespondenz stehen.)

Der Input lässt sich als partiell spezifizierte F-Struktur fassen (vgl. Bresnan 2000). Mögliche Kandidaten – Paare aus C-Struktur und F-Struktur – werden durch eine LFG-artige formale Grammatik definiert, in der die unverletzbaren Prinzipien kodiert sind und die deshalb G_{inviol} genannt wird. Diese Grammatik implementiert im wesentlichen eine erweiterte X-bar-Theorie (Bresnan 2001, ch. 6). Lexikalische Kategorien (wie V) und funktionale Kategorien (wie I und C) werden auf dieselbe F-Struktur abgebildet. Die Besetzung sämtlicher Positionen ist optional.

Für einen gegebenen Input wählt die Funktion *Gen* eine Teilmenge aus der durch G_{inviol} spezifizierten Menge der möglichen Kandidaten aus. Die ausschlaggebende Eigenschaft ist hier Subsumption durch die Input-F-Struktur, wobei die Kandidaten-F-Struktur auch keine über den Input hinausgehende semantische Information enthalten darf. Damit ist gewährleistet, dass alle Analysen innerhalb der Kandidatenmenge dieselbe Interpretation haben.

Die Beschränkungen werden als Schemata von strukturellen Beschreibungen der Kandidatenanalysen formalisiert. Ein Beispiel ist die Formalisierung von Beschränkung (8.6) als Schema (8.7). Der in jedem Schema enthaltene Stern ($\star$) ist eine Metavariable, die zur Beschränkungsauswertung durch jedes strukturelle Element (C-Strukturknoten und F-Strukturen) instantiiert wird. Für die sich ergebende merkmalslogische Formel wird die Erfüllbarkeit durch die Kandidatenstruktur überprüft, wobei im negativen Fall eine Verletzung der entsprechenden Beschränkung registriert wird.

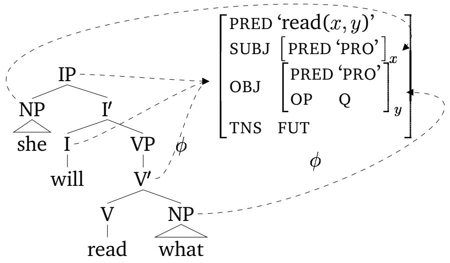
(8.6) Op-Spec: (Bresnan 2000)
Ein Operator muss auf Ebene der F-Struktur der Wert eines DF-(Diskursfunktions-)Merkmals sein.

(8.7) $(\textit{f-str}(\star) \land \exists v.[(\star\ \textsc{op}) = v]) \rightarrow \exists f.[(f\ \textsc{df}) = \star]$

"Wenn $\star$ eine F-Struktur ist, die ein Merkmal OP (mit irgendeinem Wert) enthält, so gibt es eine (andere) F-Struktur f, so dass $\star$ in f unter dem Merkmal DF eingebettet ist."

Angewandt auf die Kandidatenstruktur (8.8) (Kandidat a. in dem Tableau (8.9)) wird dieses Schema in einem Fall unerfüllbar: instantiiert man $\star$ mit der F-Struktur unter dem Merkmal OBJ, ist die linke Seite der Implikation erfüllt, nicht jedoch die rechte Seite, da die fragliche F-Struktur nicht unter DF eingebettet ist.

(8.8) *Kandidatenanalyse a. aus* (8.9)



*Op-Spec

(8.9)

Input: $\begin{bmatrix} \text{PRED} & \text{‘read}(x,y)\text{’} \\ \text{GF}_1 & \begin{bmatrix} \text{PRED} & \text{‘PRO’} \end{bmatrix}_x \\ \text{GF}_2 & \begin{bmatrix} \text{PRED} & \text{‘PRO’} \\ \text{OP} & \text{Q} \end{bmatrix}_y \\ \text{TNS} & \text{FUT} \end{bmatrix}$	OP-SPEC	OB-HD	ARG-AS-CF	DOM-HD
a. [$_{\text{IP}}$ she will [$_{\text{VP}}$ read what]]	*!			
b. [$_{\text{CP}}$ what [$_{\text{IP}}$ she will [$_{\text{VP}}$ read]]]		*!	*	
c. ☞ [$_{\text{CP}}$ what will [$_{\text{IP}}$ she [$_{\text{VP}}$ read]]]			*	*

Die Kandidaten b. und c. in (8.9),[3] bei denen *what* im Spezifikator von CP eingeführt wird, erfüllen OP-SPEC, da der Spezifikator von funktionalen Kategorien nach den Annotationsprinzipien der LFG (Bresnan 2001, sec. 6.2) unter der Funktion DF eingebettet wird. Für C′ in Kandidat b. gibt es keinen erweiterten Kopf (weder einen lokalen C-Kopf noch einen Kopf in c-kommandierender Position), daher verletzt b. die Beschränkung OB-HD. Unter der Beschränkungshierarchie für das Englische ist somit Kandidat c. der harmonischste.

Da *Gen* in der Weise definiert ist, dass alle Kandidaten vom Input subsumiert werden, können Treuebeschränkungen genauso wie die Markiertheitsbeschränkungen als Beschreibungen der Kandidatenstruktur formuliert werden – ein zusätzlicher Rückgriff auf den Input wäre redundant. Trotz der Subsumptions-Einschränkung von *Gen* kann die Inuition modelliert werden, dass Kandidaten in ihrer Oberflächenform beliebig stark vom Input abweichen können. Die Abweichung ergibt sich als Diskrepanz zwischen dem bedeutungstragenden Teil der F-Struktur und der kategoriellen und lexikalischen Realisierung (formal modelliert durch eine zusätzliche λ-Projektion). (8.10) zeigt eine Kandidatenstruktur, die die Treuebeschränkung DEP-IO verletzt.[4]

[3] Die übrigen Beschränkungen sind wie folgt definiert (vgl. (4.55), S. 89):

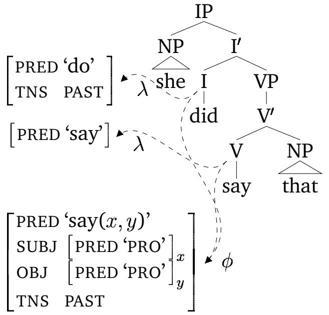
OB-HD: Jede projizierte Kategorie hat einen lexikalisch gefüllten [erweiterten, d.h., lokal X-bar-kategoriellen *oder* c-kommandierenden] Kopf. (Bresnan 2000, (21))
$(\textit{Xbar-cat}(\star) \vee \textit{Xmax-cat}(\star)) \rightarrow \exists n.[\textit{ext-hd}(n,\star)]$

ARG-AS-CF: Argumente stehen in C-Struktur-Positionen, die in der F-Struktur auf Komplementfunktionen abgebildet werden.
$\exists f.[(f\ \text{CF}) = \star] \rightarrow \exists n.[\textit{cat}(n) \wedge \phi(n) = \star \wedge \textit{lex-cat}(\mathcal{M}(n))]$

DOM-HD: Wenn eine Kategorie einen erweiterten Kopf hat, dominiert sie den erweiterten Kopf.
$\forall n.[(\textit{cat}(\star) \wedge \textit{ext-hd}(n,\star)) \rightarrow \textit{dom}(\star,n)]$

[4] Das entsprechende Strukturschema lautet
$\forall n, P.[(\textit{atomic-f-str}(\star) \wedge \textit{cat}(n) \wedge (\lambda(n)\ P) = \star) \rightarrow (\phi(n)\ P) = \star]$

(8.10) *Verletzung von* DEP-IO *(die lexikalisch eingeführte Information* [PRED ‘do’] *fehlt auf F-Struktur)*



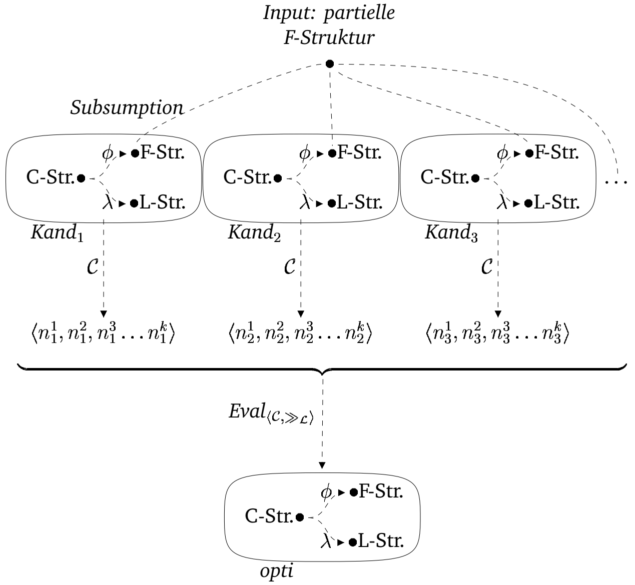
Ein formales OT-LFG System hat insgesamt die in (8.11) auf S. 224 schematisch dargestellte Struktur. Die Anwendung der Beschränkungssequenz $\mathcal{C}$ ergibt für jeden Kandidaten eine Sequenz von Verletzungszählern. Aufgrund der Beschränkungsverletzungen der Kandidaten und in Abhängigkeit von der sprachspezifischen Hierarchie $\gg_{\mathcal{C}}$ bestimmt Evaluierungsfunktion *Eval* den oder die optimalen Kandidaten.

Die von einem solchen System generierte Sprache ist als die Menge der Analysen aus G_{inviol} definiert, für die ein Input existiert, zu dem sie sich als optimaler Kandidat ergeben. Die Existenzquantifikation ist später vor allem für Überlegungen zur Verarbeitung von Belang: um die Zugehörigkeit eines Strings zur Sprache zu überprüfen, müssen alle möglichen zugrundeliegenden Input-Repräsentationen in Betracht gezogen werden.

5 Die Richtung der Optimierung

Ein eng verwandtes formales System ergibt sich, wenn zur Definition der Kandidatenmenge nicht eine zugrundeliegende bedeutungsnahe Repräsentation angesetzt wird, sondern der Oberflächen-String aus der C-Struktur. Die naheliegende Interpretation des sich hieraus ergebenden Konzepts der Optimalität ist die *Bevorzugung* der Lesart eines ambigen Strings. Diese umgekehrte Optimierung wird als interpretive oder verstehensbasierte (*comprehension-based*) Optimierung bezeichnet. Entsprechend heißt die klassische Optimierung expressiv oder produktionsbasiert.

(8.11) *Die Gesamtstruktur eines produktionsbasierten OT-LFG-Systems*


Input: partielle
F-Struktur
Subsumption
C-Str.
φ
F-Str.
λ
L-Str.
...
Kand$_1$
Kand$_2$
Kand$_3$
$\mathcal{C}$
$\langle n_1^1, n_1^2, n_1^3 \dots n_1^k \rangle$
$\langle n_2^1, n_2^2, n_2^3 \dots n_2^k \rangle$
$\langle n_3^1, n_3^2, n_3^3 \dots n_3^k \rangle$
Eval$_{\langle \mathcal{C}, \gg_{\mathcal{C}} \rangle}$
opti

Betrachtet man das Phänomen des Einfrierens von Wortstellungsvariationen (*Word order freezing*, vgl. Kuhn 2001a, 4.2, Lee 2001), so zeigt sich, dass mit der verstehensbasierten Optimierung sinnvolle linguistische Vorhersagen gemacht werden können, insbesondere auch dann, wenn dieselben Beschränkungen wie in der produktionsbasierten Optimierung eingesetzt werden. Allerdings erweist sich die syntaktische Teilaufgabe innerhalb der gesamtkognitiven Desambiguierungsaufgabe als schwer abgrenzbar. Der Diskurskontext, der extralinguistische Kontext und enzyklopädisches Wissen interagieren mit grammatischen Eigenschaften der Kandidaten. Für Überlegungen zur Formalisierung hat dies zur Folge, dass noch weitgehend unklar ist, welches ein gangbarer Weg für die explizite Modellierung eines nicht-trivialen Datenfragments ist. Der Schluss, dass der OT-Ansatz mit seiner Rankierung von Beschränkungen (im Gegensatz zu einer Gewichtung) für die verstehensbasierten Optimierung gänzlich ungeeignet ist, scheint aber verfrüht. Ein OT-Modell mit einem für alle Kandidaten fixierten Kontext erlaubt möglicherweise eine geeignete Isolierung der syntaktischen Desambiguierungsaufgabe.

Die Kombination der beiden “Richtungen” der Optimierung führt zu einem sogenannten bidirektionalen Optimierungsmodell (vgl. z.B. Wilson 2001; Smolensky 1998; Lee 2001; Blutner 2000). Für die Verknüpfung der beiden Optimierungen besteht ein Spielraum: das *Grammatikalitäts-/Präferenz-Modell* hält an der rein produktionsbasierten Definition von Grammatikalität fest und nutzt die verstehensbasierte Optimierung nur zur Auswahl zwischen in diesem Sinne grammatischen String-Analysen. Das *stark bidirektionale Optimierungsmodell* definiert Wohlgeformtheit als Optimalität in beiden Richtungen und ist somit restriktiver: eine Konkurrenzanalyse A des zu untersuchenden Strings kann im letzteren Modell auch dann die produktionsbasiert optimale Lesart B blockieren (d.h. suboptimal und deshalb unakzeptabel machen), wenn A selbst nicht produktionsbasiert optimal ist. Nach dem Grammatikalitäts/Präferenz-Modell wäre A nicht grammatisch und deshalb nicht Teilnehmer des verstehensbasierten Wettbewerbs. B würde also als grammatisch und präferiert vorhergesagt.

Das stark bidirektionale Modell ist formal elegant und erlaubt eine einfache Ableitung von sprachspezifischer Unaussprechbarkeit (vgl. Kapitel 3). Allerdings schränkt das starke Optimalitätskonzept auch den Raum für generalisierende Erklärungsansätze ein. In einem schwächeren bidirektionalen Modell (vgl. z.B. Blutner 2000) kann eine Interaktion zwischen den Optimierungsrichtungen für eine Vereinfachung der benötigten Beschränkungsmenge eingesetzt werden. Im Abschnitt 5.3.2 wird dies verdeutlicht, indem die Möglichkeit zur Vereinfachung der *pro-drop*-Analyse nach Grimshaw and Samek-Lodovici (1998) demonstriert wird. Ein schwach bidirektionales Modell, basierend auf einem kandidatenübergreifend fixierten Kontext, erlaubt die Ableitung einer Erschließbarkeitsbedingung (*Recoverability*) aus Beschränkungsinteraktion.

6 Komputationelle OT

Soll die LFG-basierte Formalisierung von OT-Syntax komputationell umgesetzt werden, stellen sich einige Fragen. Für uneingeschränkte OT-Systeme ist im allgemeinen unentscheidbar, ob ein String zur generierten Sprache gehört (Johnson 1998, vgl. auch Abschnitt 4.2.2 in der vorliegenden Arbeit). Zentral ist zum einen die Frage nach dem Umgang mit infiniten Kandidatenmengen und zum anderen die Umkehrung der Verarbeitungsrichtung für die Parsing- bzw. Erkennungsaufgabe (*Recognition*). Die Umkehrung der Verarbeitungsrichtung wird bereits beim klassischen unidirektionalen Modell erforderlich: Die vom OT-Modell erzeugte Sprache ist produktionsbasiert definiert, d.h., für jedes als zugrundeliegend angenommene Input muss eine Kandidatenmenge in Generierungsrichtung erzeugt werden, um die Optimalität der vorgefundenen Oberflächenform zu verifizieren.

Da das OT-LFG-Modell auf dem komputationell gut untersuchten Formalismus der LFG aufbaut, gibt es eine naheliegende Antwort auf die Fragen: Durch die Art und Weise, wie *Gen* und die Beschränkungen formal definiert sind, lassen sich dann die Ergebnisse von komputationellen Betrachtungen und Verarbeitungsverfahren in der Tat auf das OT-LFG-Modell übertragen. Insbesondere die Erkenntnis, dass die Menge der aus einer F-Struktur generierten Strings eine kontextfreie Menge ist (Kaplan and Wedekind 2000), lässt sich für das Generierungsproblem innerhalb der OT ausnutzen. Das Problem der infiniten Kandidatenmenge kann damit gelöst werden. Eine Erweiterung der Kaplan-Wedekind-Konstruktion wird eingeführt, und die Entscheidbarkeit des Generierungsproblems für OT-LFG-Systeme wird bewiesen.

Auch die Umkehrung der Verarbeitungsrichtung lassen sich Ergebnisse aus der klassischen LFG ausnutzen. Durch die Umkehrung der Verarbeitungsrichtung für die Parsing- bzw. Erkennungsaufgabe kann die Behandlung von beliebigen DEP-IO- und MAX-IO-Verletzungen allerdings nur in einem stark bidirektionalen Optimierungsmodell sichergestellt werden. Für ein schwächeres Konzept von bidirektionaler Optimierung ist die Parsing-Aufgabe semi-entscheidbar. Problematisch sind stark elliptische Äußerungen in einer treuebasierten OT-Analyse von Ellipse.

(8.12) Weich glaubt Hans (Klein 1993, 763)

Hier sind jedoch auch die Grammatikalitätsurteile von Muttersprachlern vom Umfang des offengelegten Diskurskontexts abhängig, wie ein Vergleich von (8.12) in Isolation und im Kontext (*Wie mag Otto seine Eier zum Früstück?*) zeigt. Daher mag die Semi-Entscheidbarkeit der Parsing-Aufgabe im OT-Modell der realen Komplexität der Aufgabe nahekommen. Für ein kontextuell eingeschränktes OT-System wird die Entscheidbarkeit der Parsing-Aufgabe bewiesen.

7 Schlussbemerkung

Zur angestrebten Verwendung des OT-Ansatzes als Basis für eine stärker datenorientierte linguistische Theorie und deren computerlinguistische Umsetzung trägt diese Arbeit eine Formalisierung von OT-Syntax im streng nicht-deklarativen Rahmen der LFG bei. Für den LFG-Formalismus stehen sehr gut entwickelte Parsing- und Generierungssystem bereit (vor allem das *Xerox Linguistic Environment*, XLE), so dass theoretische Analyseideen schnell und originalgetreu umgesetzt und auf eine breite Datenbasis angewandt werden können.

Interessant ist in diesem Zusammenhang ein Vergleich mit probabilistischen Verfahren, die z.T. ebenfalls auf den Repräsentationen der LFG aufsetzen (vgl. Johnson, Geman, Canon, Chi, and Riezler 1999; Riezler, Prescher, Kuhn, and Johnson 2000). Wie Johnson (1998) bemerkt, sind die dabei eingesetzten log-linearen Modelle formal nah mit der Beschränkungsidee des OT-Ansatzes verwandt. Allerdings beschränkt sich der Einsatz in der statistischen Sprachverarbeitung bislang auf das Analogon der *verstehensbasierten* Optimierung zur Desambiguierung. Eine Analysegrammatik des Englischen oder Deutschen wird vorausgesetzt (bzw. eine detaillierte syntaktische Annotation der Trainingsdaten). In einem vollständigen OT-System sollte auch die Analysegrammatik – modelliert durch produktionsbasierte Optimierung – aus Daten gelernt werden.

Wie diese Arbeit aufzeigt, sind allerdings zu einer Reihe von Details – insbesondere zur bidirektionalen Optimierung – weitergehende empirische und formale Untersuchungen erforderlich, damit ein linguistisch angemessenes Wettbewerbsmodell auf breiter empirischer Basis trainiert und eingesetzt werden kann.

Bibliography

Abraham, W. (1986). Word order in the middle field of the German sentence. In W. Abraham and S. de Meij (Eds.), *Topic, Focus, and Configurationality*, pp. 15–38.

Ackema, P. and A. Neeleman (1998). Optimal questions. *NLLT 16*, 443–490.

Aissen, J. (1999). Markedness and subject choice in Optimality Theory. *Natural Language and Linguistic Theory 17*, 673–711.

Andrews, A. D. and C. D. Manning (1999). *Complex Predicates and Information Spreading in LFG*. Stanford, CA: CSLI Publications.

Asudeh, A. (1999). Linking, optionality, and ambiguity in Marathi: An Optimality Theory analysis. Ms. Stanford University. Department of Linguistics.

Beaver, D. (2000). The optimization of discourse. Ms., Stanford University.

Blackburn, P. and E. Spaan (1993). A modal perspective on the computational complexity of attribute value grammar. *Journal of Logic, Language, and Information 2*(2), 129–169.

Blutner, R. (2000). Some aspects of optimality in natural language interpretation. Ms., Humboldt University Berlin.

Boersma, P. (1998). *Functional Phonology. Formalizing the interactions between articulatory and perceptual drives*. Ph. D. thesis, University of Amsterdam.

Boersma, P. and B. Hayes (2001). Empirical tests of the gradual learning algorithm. *Linguistic Inquiry 32*(1), 45–86.

Bresnan, J. (1996). LFG in an OT setting: Modelling competition and economy. In M. Butt and T. H. King (Eds.), *Proceedings of the First LFG Conference*, CSLI Proceedings Online.

Bresnan, J. (1999). The emergence of the unmarked pronoun. To appear in *Optimality-theoretic Syntax*, ed. by G. Legendre, S. Vikner, and J. Grimshaw, The MIT Press.

Bresnan, J. (2000). Optimal syntax. In J. Dekkers, F. van der Leeuw, and J. van de Weijer (Eds.), *Optimality Theory: Phonology, Syntax, and Acquisition*. Oxford University Press.

Bresnan, J. (2001). *Lexical-Functional Syntax*. Oxford: Blackwell.

Butt, M., S. Dipper, A. Frank, and T. H. King (1999). Writing large-scale parallel grammars for English, French, and German. In M. Butt and T. H. King (Eds.), *Proceedings of the LFG99 Conference, Manchester, UK*, CSLI Proceedings Online.

Butt, M., T. King, M.-E. Niño, and F. Segond (1999). *A Grammar Writer's Cookbook*. Number 95 in CSLI Lecture Notes. Stanford, CA: CSLI Publications.

Choi, H.-W. (1999). *Optimizing Structure in Context: Scrambling and Information Structure*. CSLI Publications.

Chomsky, N. (1981). *Lectures on Government and Binding*. Dordrecht: Foris.

Chomsky, N. (1995). *The Minimalist Program*. Cambridge, MA: MIT Press.

Dalrymple, M. (Ed.) (1999). *Semantics and Syntax in Lexical Functional Grammar: The Resource Logic Approach*. Cambridge, MA: MIT Press.

Dalrymple, M. (Ed.) (2001). *Lexical Functional Grammar*, Volume 34 of *Syntax and Semantics*. New York: Academic Press.

Dalrymple, M., R. M. Kaplan, J. T. Maxwell, and A. Zaenen (Eds.) (1995). *Formal Issues in Lexical-Functional Grammar*. Stanford, CA: CSLI Publications.

Dalrymple, M., J. Lamping, F. Pereira, and V. Saraswat (1997). Quantifiers, anaphora, and intensionality. *Journal of Logic, Language, and Information 6*, 219–273.

Dalrymple, M., J. Lamping, and V. Saraswat (1993). LFG semantics via constraints. In *Proceedings of EACL, University of Utrecht*, pp. 97–105.

Dymetman, M. (1991). Inherently reversible grammars, logic programming and computability. In *Proceedings of the ACL Workshop: Reversible Grammar in Natural Language Processing*, Berkeley, pp. 20–30.

Dymetman, M. (1997). Charts, interaction-free grammars, and the compact representation of ambiguity. In *Proceedings of IJCAI-97*.

Eisner, J. (1997). Efficient generation in primitive optimality theory. In *Proceedings of the ACL 1997*, Madrid. Rutgers Optimality Archive, `http://ruccs.rutgers.edu/roa.html` (ROA-206-0797).

Ellison, M. (1994). Phonological derivation in optimality theory. In *COLING 1994*, Kyoto, Japan, pp. 1007–1013. Rutgers Optimality Archive, `http://ruccs.rutgers.edu/roa.html` (ROA-75-0000).

Falk, Y. N. (2001). *Lexical-Functional Grammar: An Introduction to Parallel Constraint-Based Syntax*. Stanford, CA: CSLI Publications.

Fanselow, G., M. Schlesewsky, D. Cavar, and R. Kliegl (1999). Optimal parsing, syntactic parsing preferences, and Optimality Theory. Ms., Rutgers Optimality Archive, `http://ruccs.rutgers.edu/roa.html` (ROA-367-1299).

Frank, A., T. H. King, J. Kuhn, and J. Maxwell (1998). Optimality Theory style constraint ranking in large-scale LFG grammars. In M. Butt and T. H. King (Eds.), *Proceedings of the Third LFG Conference*, CSLI Proceedings Online.

Frank, A., T. H. King, J. Kuhn, and J. Maxwell (2001). Optimality Theory style constraint ranking in large-scale LFG grammars. In P. Sells (Ed.), *Formal and Empirical Issues in Optimality-theoretic Syntax*, pp. 367–397. Stanford, CA: CSLI Publications.

Frank, R. and G. Satta (1998). Optimality theory and the generative complexity of constraint violation. *Computational Linguistics 24*(2), 307–316.

Gerdemann, D. and G. van Noord (2000). Approximation and exactness in finite state Optimality Theory. In *SIGPHON 2000, Finite State Phonology. Proceedings of the Fifth Workshop of the ACL Special Interest Group in Computational Phonology*, Luxembourg.

Gibson, E. and K. Broihier (1998). Optimality Theory and human sentence processing. In P. Barbosa, D. Fox, P. Hagstrom, M. McGinnis, and D. Pesetsky (Eds.), *Is the Best Good Enough?*, pp. 157–191. MIT Press and MITWPL.

Grimshaw, J. (1991). Extended projection. Unpublished Manuscript, Brandeis University.

Grimshaw, J. (1997). Projection, heads, and optimality. *Linguistic Inquiry 28*(3), 373–422.

Grimshaw, J. (1998). Constraints on constraints in Optimality Theoretic syntax. Manuscript, Rutgers University.

Grimshaw, J. and V. Samek-Lodovici (1998). Optimal subjects and subject universals. In P. Barbosa, D. Fox, P. Hagstrom, M. McGinnis, and D. Pesetsky (Eds.), *Is the Best Good Enough?*, pp. 193–219. MIT Press.

Haegeman, L. (1994). *Introduction to Government and Binding Theory* (2nd ed.). Oxford: Blackwell.

Hale, M. and C. Reiss (1998). Formal and empirical arguments concerning phonological acquisition. *Linguistic Inquiry* (29), 656–683.

Hammond, M. (1997). Parsing syllables: modeling OT computationally. Rutgers Optimality Archive, `http://ruccs.rutgers.edu/roa.html` (ROA-222-1097).

Heck, F., G. Müller, R. Vogel, S. Fischer, S. Vikner, and T. Schmid (2000). On the nature of the input in Optimality Theory. Manuscript, University of Stuttgart.

Hendriks, P. and H. de Hoop (1999). Optimality Theoretic semantics. *Linguistics and Philosohpy*. to appear.

Höhle, T. (1982). Explikation für 'normale Betonung' und 'normale Wortstellung'. In W. Abraham (Ed.), *Satzglieder im Deutschen*. Tübingen: Gunther Narr Verlag.

Jäger, G. (2000). Some notes on the formal properties of bidirectional Optimality Theory. Ms., ZAS Berlin, Rutgers Optimality Archive, `http://ruccs.rutgers.edu/roa.html` (ROA-414-09100).

Johnson, M. (1988). *Attribute-Value Logic and the Theory of Grammar*. Stanford, CA: CSLI.

Johnson, M. (1998). Optimality-theoretic Lexical Functional Grammar. In *Proceedings of the 11th Annual CUNY Conference on Human Sentence Processing, Rutgers University*. To appear.

Johnson, M., S. Geman, S. Canon, Z. Chi, and S. Riezler (1999). Estimators for stochastic "unification-based" grammars. In *Proceedings of the 37th Annual Meeting of the Association for Computational Linguistics (ACL'99), College Park, MD*, pp. 535–541.

Kager, R. (1999). *Optimality Theory*. Cambridge: Cambridge University Press.

Kamp, H. (1981). A theory of truth and semantic representation. In J. Groenendijk, T. Janssen, and M. Stokhof (Eds.), *Formal Methods in the Study of Language*.

Kamp, H. (1990). Prolegomena to a structural theory of belief and other attitudes. In C. A. Anderson and J. Owens (Eds.), *Propositional Attitudes*. Stanford, CA: CSLI.

Kamp, H. and U. Reyle (1993). *From Discourse to Logic. Introduction to Modeltheoretic Semantics of Natural Language, Formal Logic and Discourse Representation Theory*. Dordrecht: Kluwer.

Kaplan, R. M. (1995). The formal architecture of Lexical-Functional Grammar. In M. Dalrymple, R. M. Kaplan, J. T. Maxwell, and A. Zaenen (Eds.), *Formal Issues in Lexical-Functional Grammar*. Stanford, CA: CSLI Publications. Originally appeared in *Proceedings of ROCLING II*, ed. C.-R. Huang and K.-J. Chen (Taipei, Republic of China, 1989), 1-18.

Kaplan, R. M. and J. W. Bresnan (1982). Lexical-Functional Grammar: a formal system for grammatical representation. In J. W. Bresnan (Ed.), *The Mental Representation of Grammatical Relations*, Chapter 4, pp. 173–281. Cambridge, MA: MIT Press.

Kaplan, R. M. and J. T. Maxwell (1988). An algorithm for functional uncertainty. In *Proceedings of COLING-88*, Budapest, pp. 297–302. Reprinted in Dalrymple et al. (1995), pp. 177-197.

Kaplan, R. M. and J. T. Maxwell (1996). LFG grammar writer's workbench. Technical report, Xerox PARC. `ftp://ftp.parc.xerox.com/pub/lfg/`.

Kaplan, R. M. and J. Wedekind (2000). LFG generation produces context-free languages. In *Proceedings of COLING-2000*, Saarbrücken, pp. 297–302.

Kaplan, R. M. and A. Zaenen (1989/95). Long-distance dependencies, constituent structure, and functional uncertainty. In M. Dalrymple, R. M. Kaplan, J. T. Maxwell, and A. Zaenen (Eds.), *Formal Issues in Lexical-Functional Grammar*, pp. 137–165. Stanford, CA: CSLI Publications. Originally appeared in *Alternative Conceptions of Phrase Structure*, ed. M. Baltin and A. Kroch (Chicago: Chicago University Press, 1989) 17–42.

Karttunen, L. (1998). The proper treatment of optimality in computational phonology. In *Proceedings of the International Workshop on Finite-State Methods in Natural Language Processing, FSMNLP'98*, pp. 1–12. To appear, ROA-258-0498.

Kay, M. (1996). Chart generation. In *Proceedings of the 34th Annual Meeting of the Association for Computational Linguistics, Santa Cruz, CA*.

Keller, B. (1993). *Feature Logics, Infinitary Descriptions and Grammar*. Stanford, CA: CSLI.

Keller, F. (2000). *Gradience in Grammar: Experimental and Computational Aspects of Degrees of Grammaticality*. Ph. D. thesis, University of Edinburgh.

Keller, F. and A. Asudeh (2001). Probabilistic learning algorithms and Optimality Theory. Unpublished Ms., Saarbrücken, Stanford University.

King, T. H., S. Dipper, A. Frank, J. Kuhn, and J. Maxwell (2000). Ambiguity management in grammar writing. In E. Hinrichs, D. Meurers, and S. Wintner (Eds.), *Proceedings of the Workshop on Linguistic Theory and Grammar Implementation, ESSLLI-2000, Birmingham, UK*.

Klein, W. (1993). Ellipse. In J. Jacobs, A. von Stechow, W. Sternefeld, and T. Vennemann (Eds.), *Syntax: An International Handbook of Contemporary Research*, pp. 763–799. Berlin: de Gruyter.

Kuhn, J. (1995). Information packaging in German – some motivation from HPSG-based translation. Ms. Centre for Cognitive Science, University of Edinburgh.

Kuhn, J. (1996a). Context effects on interpretation and intonation. In D. Gibbon (Ed.), *Natural Language Processing and Speech Technology. Results of the 3rd KONVENS Conference*, pp. 186–198. Berlin: de Gruyter.

Kuhn, J. (1996b). On intonation and interpretation in context – is there a unitary explanation for focus and deaccenting? Diplomarbeit, Institut für maschinelle Sprachverarbeitung, Universität Stuttgart.

Kuhn, J. (1996c). An underspecified HPSG representation for information structure. In *Proceedings of COLING-96*, Copenhagen, pp. 670–675.

Kuhn, J. (1998). Towards data-intensive testing of a broad-coverage LFG grammar. In B. Schröder, W. Lenders, W. Hess, and T. Portele (Eds.), *Computers, Linguistics, and Phonetics between Language and Speech, Proceedings of the 4th Conference on Natural Language Processing – KONVENS-98*, pp. 43–56. Bonn: Peter Lang.

Kuhn, J. (1999a). The syntax and semantics of split NPs in LFG. In F. Corblin, C. Dobrovie-Sorin, and J.-M. Marandin (Eds.), *Empirical Issues in Formal Syntax and Semantics 2, Selected Papers from the Colloque de Syntaxe et Sémantique à Paris (CSSP 1997)*, pp. 145–166. The Hague: Thesus.

Kuhn, J. (1999b). Towards a simple architecture for the structure-function mapping. In M. Butt and T. H. King (Eds.), *Proceedings of the LFG99 Conference, Manchester, UK*, CSLI Proceedings Online.

Kuhn, J. (2000a). Faithfulness violations and bidirectional optimization. In M. Butt and T. H. King (Eds.), *Proceedings of the LFG 2000 Conference, Berkeley, CA*, CSLI Proceedings Online, pp. 161–181.

Kuhn, J. (2000b). Processing Optimality-theoretic syntax by interleaved chart parsing and generation. In *Proceedings of the 38th Annual Meeting of the Association for Computational Linguistics (ACL-2000)*, Hongkong, pp. 360–367.

Kuhn, J. (2001a). Generation and parsing in Optimality Theoretic syntax – issues in the formalization of OT-LFG. In P. Sells (Ed.), *Formal and Empirical Issues in Optimality-theoretic Syntax*, pp. 313–366. Stanford, CA: CSLI Publications.

Kuhn, J. (2001b). Optimality-theoretic syntax – a chart-based approach to parsing and generation. In C. Rohrer, A. Roßdeutscher, and H. Kamp (Eds.), *Linguistic Form and its Computation*, pp. 353–385. Stanford, CA: CSLI Publications.

Kuhn, J. (2001c). Resource sensitivity in the syntax-semantics interface and the German split NP construction. In W. D. Meurers and T. Kiss (Eds.), *Constraint-Based Approaches to Germanic Syntax*, pp. 177–215. Stanford, CA: CSLI Publications.

Kuhn, J. and C. Rohrer (1997). Approaching ambiguity in real-life sentences – the application of an Optimality Theory-inspired constraint ranking in a large-scale LFG grammar. In *Proceedings of DGfS-CL*, Heidelberg.

Lee, H. (2000). The emergence of the unmarked order in Hindi. In *Proceedings of NELS 30, October 1999, Rutgers, NJ*, Amherst, MA. Graduate Linguistics Students' Association.

Lee, H. (2001). Markedness and word order freezing. In P. Sells (Ed.), *Formal and Empirical Issues in Optimality-theoretic Syntax*. Stanford, CA: CSLI Publications. To appear.

Legendre, G., W. Raymond, and P. Smolensky (1993). An optimality-theoretic typology of case and grammatical voice systems. In *Proceedings of the 19th Meeting of the Berkeley Linguistics Society*.

Legendre, G., P. Smolensky, and C. Wilson (1998). When is less more? Faithfulness and minimal links in *wh*-chains. In P. Barbosa, D. Fox, P. Hagstrom, M. McGinnis, and D. Pesetsky (Eds.), *Is the Best Good Enough? Optimality and Competition in Syntax*, pp. 249–289. Cambridge, MA: MIT press.

Lenerz, J. (1977). *Zur Abfolge nominaler Satzglieder im Deutschen*. Tübingen: Gunther Narr Verlag.

Levin, L. S. (1982). Sluicing: A lexical interpretation procedure. In J. W. Bresnan (Ed.), *The Mental Representation of Grammatical Relations*, Chapter 9, pp. 590–654. Cambridge, MA: MIT Press.

Maxwell, J. and R. Kaplan (1998). Unification-based parsers that automatically take advantage of context freeness. Ms., Xerox PARC, February 1998.

McCarthy, J. J. and A. Prince (1995). Faithfulness and reduplicative identity. In J. Beckman, L. W. Dickey, and S. Urbanczyk (Eds.), *University of Massachusetts Occasional Papers, Volume 18: Papers in Optimality Theory*, pp. 249–384. Amherst, MA: Graduate Linguistics Students' Association.

Morimoto, Y. (2000). “Crash vs. Yield”: On the conflict asymmetry in syntax and phonology. Ms. Stanford University.

Müller, G. (1998). German word order and Optimality Theory. Working paper no. 126, SFB 340 Stuttgart/Tübingen.

Müller, G. (1999). Optionality in Optimality-Theoretic syntax. *GLOT International 4*(5), 3–8.

Neumann, G. (1994). *A uniform computational model for natural language parsing and generation*. Ph. D. thesis, Universität des Saarlandes, Germany.

Neumann, G. (1998). Interleaving natural language parsing and generation through uniform processing. *Artifical Intelligence 99*, 121–163.

Pereira, F. and D. Warren (1983). Parsing as deduction. In *Proceedings of the 21st Annual Meeting of the Association for Computational Linguistics, Cambridge, MA*.

Pesetsky, D. (1998). Some optimiality principles of sentence pronunciation. In P. Barbosa, D. Fox, P. Hagstrom, M. McGinnis, and D. Pesetsky (Eds.), *Is the Best Good Enough? Optimality and Competition in Syntax*, pp. 337–383. Cambridge, MA: MIT press.

Pollard, C. J. and I. A. Sag (1994). *Head-Driven Phrase Structure Grammar*. Studies in Contemporary Linguistics. Chicago, London: University of Chicago Press.

Prince, A. and P. Smolensky (1993). Optimality Theory: Constraint interaction in generative grammar. Technical Report Technical Report 2, Rutgers University Center for Cognitive Science.

Riezler, S., D. Prescher, J. Kuhn, and M. Johnson (2000). Lexicalized stochastic modeling of constraint-based grammars using log-linear measures and EM training. In *Proceedings of the 38th Annual Meeting of the Association for Computational Linguistics (ACL'00), Hong Kong*, pp. 480–487.

Samek-Lodovici, V. (1996). *Constraints on Subjects: An Optimality Theoretic Analysis*. Ph. D. thesis, Rutgers University.

Schmid, T. (2001). OT accounts of optionality: A comparison of global ties and neutralization. In G. Müller and W. Sternefeld (Eds.), *Competition in Syntax*, pp. 283–319. Mouton de Gruyter. To appear.

Sells, P. (1999). Constituent order as alignment. In S. Kuno et al. (Eds.), *Harvard Studies in Korean Linguistics 8*, pp. 546–560. Harvard University.

Sells, P. (2001). *Alignment Constraints in Swedish Clausal Syntax*. Stanford, CA: CSLI Publications.

Shieber, S. (1985). Using restriction to extend parsing algorithms for complex-feature-based formalisms. In *Proceedings of the 23rd Annual Meeting of the Association for Computational Linguistics, Chicago, IL*.

Shieber, S. (1988). A uniform architecture for parsing and generation. In *Proceedings of the 12th International Conference on Computational Linguistics (COLING), Budapest*.

Smolensky, P. (1996). On the comprehension/production dilemma in child language. *Linguistic Inquiry 17*, 720–731.

Smolensky, P. (1998). Why syntax is different (but not really): Ineffability, violability and recoverability in syntax and phonology. Handout of a talk given at the workshop *Is Syntax Different?* at Stanford University, December 1998.

Sternefeld, W. (1997). Comparing reference sets. In M. Bierwisch, H.-M. Gärtner, and C. Wilder (Eds.), *Economy in Linguistic Theory*, pp. 81–114. Berlin: Akademieverlag.

Tesar, B. (1995). *Computational Optimality Theory*. Ph. D. thesis, University of Colorado.

Tesar, B. B. and P. Smolensky (1998). Learnability in Optimality Theory. *Linguistic Inquiry 29*(2), 229–268.

Uszkoreit, H. (1987). *Word Order and Constituent Structure in German*. CSLI Lecture Notes. Stanford, CA: CSLI.

Varges, S. (1997). Parsing und Generierung in uniformen Architekturen. Master's thesis, Heinrich-Heine-Universität Düsseldorf.

Wartena, C. (2000). A note on the complexity of optimality systems. Ms. Universität Potsdam, Rutgers Optimality Archive, `http://ruccs.rutgers.edu/roa.html` (ROA-385-03100).

Wedekind, J. (1995). Some remarks on the decidability of the generation problem in LFG- and PATR-style unification grammars. In *Proceedings of the 7th EACL Conference*, Dublin, pp. 45–52.

Wedekind, J. (1999). Semantic-driven generation with LFG- and PATR-style grammars. *Computational Linguistics 25*(2), 277–281.

Wedekind, J. and R. M. Kaplan (1993). Type-driven semantic interpretation of f-structures. In *Proceedings of EACL, University of Utrecht*.

Wilson, C. (2001). Bidirectional optimization and the theory of anaphora. In J. Grimshaw, G. Legendre, and S. Vikner (Eds.), *Optimality Theoretic Syntax*. Cambridge, MA: MIT Press. To appear.

Zeevat, H. (2000). The asymmetry of Optimality Theoretic syntax and semantics. Ms., University of Amsterdam.