Theorie des Lexikons

Arbeiten des Sonderforschungsbereichs 282

Nr. 88

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A construction-kit approach to Optimality Theory implementation

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Oktober 1996

Projekt C6

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OT SIMPLE – a construction-kit approach to Optimality Theory implementation

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Abstract

This paper details a simple approach to the implementation of Optimality Theory (OT, Prince and Smolensky 1993) on a computer, in part reusing standard system software. In a nutshell, OT's GENerating source is implemented as a BinProlog program interpreting a context-free specification of a GEN structural grammar according to a user-supplied input form. The resulting set of textually flattened candidate tree representations is passed to the CONstraint stage. Constraints are implemented by finite-state transducers specified as 'sed' stream editor scripts that typically map ill-formed portions of the candidate to violation marks. EVALuation of candidates reduces to simple sorting: the violation-mark-annotated output leaving CON is fed into 'sort', which orders candidates on the basis of the violation vector column of each line, thereby bringing the optimal candidate to the top. This approach gave rise to OT SIMPLE, the first freely available software tool for the OT framework to provide generic facilities for both GEN and CONstraint definition. Its practical applicability is demonstrated by modelling the OT analysis of apparent subtractive pluralization in Upper Hessian presented in Golston and Wiese (1996).

Contents

1 Introduction

This paper shows how to implement classical Optimality Theory (OT, Prince and Smolensky 1993) in a particularly simple fashion on a computer.[1]

OT is an important emergent theoretical paradigm in linguistics that by now underlies much research in both phonology and morphology, while already being assumed in some work in syntax as well.[2] For convenience, we nevertheless provide a quick overview of the key features of this new theoretical paradigm in what follows, with an eye towards its technical side.

1.1 Optimality Theory in a nutshell

OT proposes a general framework for the theoretical analysis of natural language phenomena. In OT's conceptual model of natural language computation, an underlying input form is first structurally enriched by a distinguished component called GEN, yielding a possibly infinite set of structured output candidates. OT per se is not committed to specific assumptions regarding substantive aspects of the range and nature of the structure assigned to inputs, but one of the requirements for GEN formulated so far, 'Freedom of Analysis' (McCarthy and Prince 1993) in effect demands that it should be sufficiently inclusive and rich.

Candidates are then judged by an ensemble of universal wellformedness constraints, named the CON set in OT terminology. Judgement consists of pairing each candidate with a violation vector that records the degree to which the candidate deviates from the wellformedness perspective imposed by each constraint. As a graphical rendering of degree of violation, OT usually employs strings of asterisks, each asterisk or violation mark indicating a constraint-specific unit of violation. Depending on the nature of the constraint in question, such violation may be *binary*, in that substructures of a candidate are only ever classified as obeying or not obeying the constraint,

[1]The research described in this paper has been carried out in the *Sonderforschungsbereich 282 "Theorie des Lexikons", Projekt C6 Prosodische Morphologie*, funded by the German Research Agency (DFG). The author is grateful to Petra Barg, James Kilbury, Thomas Klein and Richard Wiese, both for useful comments and a thorough reading of the manuscript. The usual disclaimers apply. The latest version of the OT SIMPLE software is available on the Internet (`http://www.phil-fak.uni-duesseldorf.de/~walther/otsimple.html`).

[2]See the current OT bibliography in the electronic archive at `http://ruccs.rutgers.edu/roa.html` for a comprehensive list of papers.

emitting either no violation star or a single one per substructure. An example of this type of all-or-nothing constraint would be ONS, which states that syllables must have onsets (Prince and Smolensky 1993, 16). Alternatively, constraints may show *gradient* behaviour, typically using some abstract distance metric to calculate the deviation from an ideal, e.g. that edges of two constituents such as affix and word must coincide perfectly (cf. EDGEMOST, Prince and Smolensky 1993, p. 35). These constraint types emit a number of violation marks that is proportional to the actual distance found when assessing a candidate.[3]

According to OT, language-specific grammars differ from each other in terms of the ranking of the constraint set. The purpose of ranking, an ordering relation over CON, is to reflect the relative importance of a constraint's judgement in situations where judgements conflict with each other. As OT's strict domination regime prescribes, a candidate violating a higher-ranked constraint to a lesser degree wins over all competing candidates which incur more violation marks. Strict domination entails that the competing candidates in this scenario cannot evade their looser status by any amount of 'compensatory' non-violation w.r.t. lower-ranked constraints. However, in a situation where several candidates tie in terms of incurring the same degree of current top-most constraint violation, the entire set of those candidates is passed down to the next constraint in the hierarchy for further evaluation in the same vein, and so on recursively. Since the constraint hierarchy is assumed to be finite, the whole process is bound to terminate, in the worst case using the lowest-ranked constraint to discern winning candidates. The outcome of this evaluation procedure over violation vectors associated with candidates, EVAL,[4] then is a set of optimal output candidates for each input which minimally violate all constraints relative to the given ranking. This set of optimal candidates will often, but not necessarily, consist of a single element, the winner.

[3]Actually, as Ellison (1994b) shows, some constraints including EDGEMOST, that are described as being gradient, can be substituted by binary equivalents, but others, e.g. the members of the ALIGN constraint family cannot (cf. Ellison 1995). Another issue to be kept separate from the question of gradienthood is that binary constraints will still result in multiple violation marks per entire candidate if the substructure targeted by the constraint has multiple occurrences in the candidates (e.g. polysyllabic words for ONS).

[4]Note a slight difference in terminological meaning: While Prince and Smolensky (1993) use CON to denote the set of ranked constraints, in this paper the term is broadened to include the *action* of constraints on candidates to formally determine constraint violations. Originally this part was delegated to EVAL, which in the present setting is conversely limited to the evaluation of the violation patterns for purposes of finding the optimal candidates. The main reason for this change of meaning is that it better reflects the internal subdivision of OT SIMPLE in terms of technical components.

1.2 Motivation and previous work

While the amount of work in theoretical linguistics, in particular in the subfield of phonology, that is based on OT's conceptualization of grammar has virtually exploded over the last three years, it is surprising to see so little practical computational work that tries to formally capture GEN and CON specification on the one hand and simulate the computation of optimal candidates given such specifications on the other hand. This state of affairs probably explains in part why it is that virtually no OT work passes the formal adequacy criterion of Bird (1991), which demands that the description language used to capture generalizations, i.e. constraints, should possess a formal syntax and semantics in the strict, mathematical sense. If it were easy to specify constraints formally and check their action on GEN output by computer, the stronger claims one could then make with respect to correctness proofs and guaranteed empirical coverage would surely be an attractive selling point in anybody's analysis. Additionally, such possibilities would seem to be very promising for meaningful inter-theory comparison on the basis of a given phenomenon or corpus, since, for example, analyses couched in the inviolable constraint-based Declarative Phonology paradigm (cf. Scobbie 1991, Scobbie, Coleman, and Bird, to appear) are also frequently computer-implemented. Note that this task is different from a formal comparison of the frameworks themselves. See Ellison (1994a) for just such a comparison of Underspecification Theory and Optimality Theory, both default-based frameworks, and default-free Exception Theory, bringing out surprising similarities between the former two approaches as one of the results.

As a matter of fact, Ellison (1994b) published the first algorithm for computing with OT, assuming regular candidate sets, the most restrictive class in the well-known Chomsky hierarchy of formal languages as the formal specification language for describing both GEN(Input) and each constraint. The alphabet over which these regular sets are defined are pieces of linguistic information such as segments, syllable roles etc. paired with one of two numerical marks. The marks indicate local violation (1) or local wellformedness (0). Since the corresponding finite-state automata (FSAs), standard models of regular sets, are just special, numerically weighted graphs, constraint interaction corresponds to regular set intersection modulo a rank-sensitive concatenation of the mark vectors of two compatible graph arcs, which makes the augmented graph/FSA product operation corresponding to intersection asymmetric. A variant of a graph algorithm for solving the so-called 'shortest paths problem' for weighted graphs then forms the core of Ellison's proposal for EVAL. In brief, the term 'shortest paths' here denotes those graph arc traversals from a FSA start state to a final state which minimize the sum of violation mark vectors accumulated on the way.

While Ellison's work filled an important gap in the original conception of OT by providing the first proposal for a formal specification language for constraints and giving algorithms for *all* aspects of an OT computation from GEN input to winner set determination, an implemented and practically usable software tool that builds on Ellison's work is yet to become publicly available. [5]

Another strand of work on the problem of computing with OT is represented by Tesar (1994, 1995, 1996). In his approach, the space of possible GEN structures is encoded as a regular or context-free position structure grammar. GEN is formalized as a set of matchings between an ordered string of input segments and the terminals of the grammar, preserving the linear order of the input. A dynamic programming algorithm is used to boost efficiency in computing the optimal candidate, using the structure grammar to propose partial structures with and without faithfulness violations and assessing them via the ranked constraint set.

One important difference, when compared to Ellison's approach, is that Tesar's algorithms deal with (partial) candidates on the *object* level, albeit in a somewhat more intelligent fashion than simple enumeration, whereas Ellison is able to directly compute with an intensional *description* of the entire candidate set, subject to the weak restriction that it is formally regular. In general, an intensional approach seems more elegant and uniform, in this case employing regular sets throughout all stages of Ellison's remarkably simple algorithms, while it also has the theoretical advantage of halting even if the winner set of optimal candidates should turn out to be infinite. Faced with this situation any complete enumerating approach would not terminate, since infinite sets are not representable on the object level. Still, for the usual situation of a finite winner set the dynamic programming approach Tesar adopts to compute constraint action ensures reasonably efficient algorithmic complexity. However, from the presentation in Tesar (1995, 1996) it is not entirely clear how non-singleton winner sets are actually handled and what restrictions w.r.t. cardinality may have to be assumed. More importantly for our purposes, Tesar is not explicit on what formal description language to adopt for specifying constraints. From severe locality requirements that his

[5] However, Mark Ellison (p.c.) has done a prototype implementation by way of extending his as yet unpublished Typed Regular Description Language (TRDL) formalism. He reports that there is also work in progress at the Universities of Bielefeld and Edinburgh on implementing variants of the original proposal.

approach, unlike Ellison's, must impose on constraints,[6] it appears it should be some subset of the regular languages. Again, a practical and generally available software tool for specifying GEN and CON as well as computing a winner set via EVAL is not known to exist.

In contrast to the aforementioned general approaches to OT computation, the two implemented tools of Andrews (1995) and Hammond (1995) which *are* available focus on quite specific narrow-scale applications. While Andrews focuses on two demonstration versions of syllable theory and an application to Lardil (implementing parts of Prince and Smolensky 1993, ch.6-8), Hammond is interested in the contrastive behaviour of an OT-based syllabification strategy with rankings for English vs. French. Neither comes with a concomitant formal proposal for a sufficiently general constraint description language. Rather, GEN and the constraints of interest have been hard-wired somewhat ad hoc into the respective program code. While this is certainly a viable move for the stated purposes, one cannot expect a principled solution for the problem of general OT specification and computation to be derivable from these works.

Finally, note that a software tool developed by Raymond and Hogan (1996), despite its name *Optimality Theory Interpreter*, does not provide any means to implement GEN, constraints and constraint action – the task under focus here – restricting itself to the comparatively easier task of mechanizing EVAL. Its use is therefore limited to helping explore the consequences of reranking etc. given *human* input for GEN's output candidates and violation mark vectors.

1.3 Objectives

With this quick survey of related work in place, let us now turn to describe the major goals of OT SIMPLE, our software tool for practical OT computation. The stated objectives that should be met were defined as follows: OT SIMPLE should

- **facilitate rigid specification and testing of truly formal OT analyses**. The standard practice of graphical or natural language spec-

[6] Tesar (1996) states that for formally regular position structure grammars, a constraint must be locally evaluable on the basis of two consecutive positions in the linear position structure. For context-free position structure grammars, locality amounts to the requirement that at most one of the local tree configurations $nonterminal\_mother[nonterm._1 \ldots nonterm._N]$ or $nonterminal\_mother[terminal]$ may form the basis for deciding constraint action.

ification of constraints paired with their intuitive evaluation against a few hand-selected candidates is both error-prone and bound to fail over larger corpora and constraint sets. Put differently, human theorists on the one hand are far too smart to bother themselves with all the crazy structural possibilities in the GEN structural space or to consider every dull technical detail of every constraint during constraint evaluation in a mechanical fashion, on the other hand they are too limited resources to reliably check the zillions of candidates against a full constraint hierarchy.

- **be simple to build and reuse existing pieces of standard software**. The original OT description is intuitively simple to grasp, so a direct reflection of this simplicity in an implementation would be favourable. Reusing existing standard software minimizes coding effort and errors and helps attain greater portability to other platforms.

- **stay close to familiar operational model and conceptual entities**. Intuitions of the working linguist on how OT works are presumably shaped by the original presentation in Prince and Smolensky (1993) more than by anything else, so a user interface which overtly reflects these intuitions to a reasonably high degree should help alleviate the barrier to strict formalization and also encourage using OT SIMPLE for pedagogical purposes. It certainly would be user-friendly to see GEN actually feed into a constraint hierarchy on the screen, which assigns visible asterisks and in turn feeds into EVAL, with constituent structure displays showing the winner.

- **be sufficiently general**. One would like to be free to specify a wide range of different constraint types and have sufficient flexibility for defining the structure of GEN in order to suit the demands of a concrete analysis.

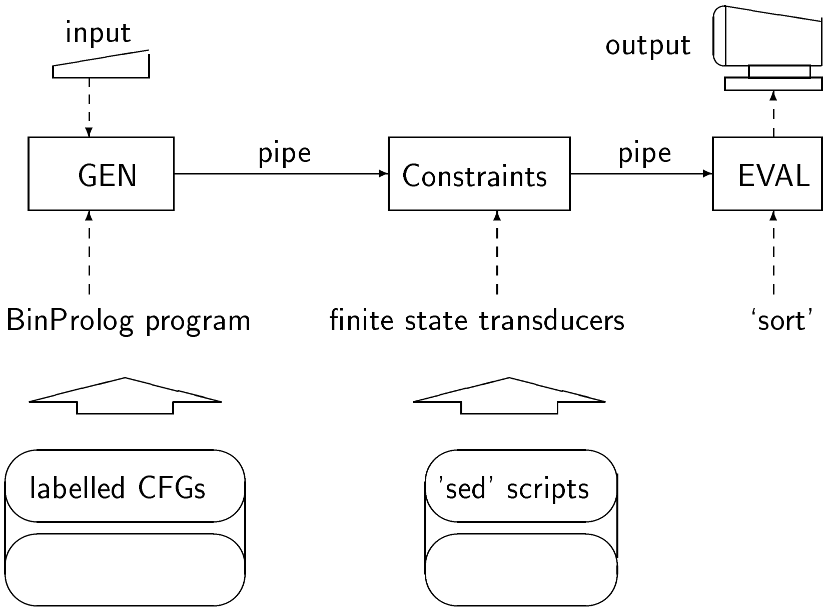
- **make reranking and inspection of intermediate stages in constraint evaluation easy**. This is a definite must for developing formal, implemented analyses incrementally, testing and debugging constraints as the theory develops. One should be able to freely rerank constraints and quickly see the effects in order to be able to experiment with factorial typologies and alternative analyses.

The next section shows in more detail to what extent these demands were met in constructing OT SIMPLE.

2 General architecture

Here is an overview of OT SIMPLE.

(1) COMPONENTS OF OT SIMPLE



Starting from left to right, GEN is realized by a BinProlog (Tarau 1992, 1996) program. Its static input takes the form of a variant of context-free grammars (CFGs), which describe the space of possible structures that can be erected over an input. CFG production rules may be labelled with mnemonic markers, to be referred to in the dynamic input to GEN, depicted above the keyboard symbol. The candidate output of GEN is in the form of tree structures, using a flattened format suitable for textual line-based representation. Each line contains one tree.

This multi-line candidate set data stream is literally fed into the next stage by means of a *pipe*. Simplifying somewhat, pipes are constructs provided by several computer operating systems (OSes), in particular, UNIX derivates, to connect the standard output of a program (which would otherwise go to the screen) to the standard input of another program (which would otherwise come from the keyboard).

The next stage provides an operational model of CON. Its main ingredient is a cascade of finite-state transducers (FSTs), one for each constraint.[7] These

[7]For an introduction to finite-state automata in general, and the special case represented by FSTs as well as the notions of regular sets and expressions used at various stages in the description of OT SIMPLE below, see e.g. Hopcroft and Ullman (1979).

are specified and cascaded using a piece of standard software called 'sed', a fast stream editor found in particular in UNIX OSes. Specifically, 'sed' provides commands for substituting parts of a line that match a given pattern by new strings. Sequences of these commands are stored in 'sed' scripts, the materialization of constraints that forms the static input to CON. Importantly, pattern descriptions can be defined using the full power of regular expressions; this gives the needed flexibility for a wide range of phonological context types, therefore constituting the essential ingredient which motivated the choice of 'sed'. Descriptions would typically characterize some illformed structural configuration, and new strings would typically contain asterisks in place of the particular configuration. After the dynamic input to CON, i.e. the multi-line candidate stream, has been enriched by 'sed' actions according to its constraint scripts, the ensuing violation-annoted output stream is again connected via a pipe to the final component, EVAL.

EVAL is nothing else than familiar sorting.[8] It uses another piece of standard software, a sorting routine named 'sort' that is again available in all UNIX OSes and elsewhere. Using 'sort' exploits the fact that we can choose both the violation symbol and its non-violation counterpart in such a way that non-violation is ordered before violation in the standard ASCII character encoding used on computers. Here, the asterisk ($*$) is the violation character and its non-violation counterpart is defined as the single quote character (').[9] Bringing the winner(s) to the top therefore amounts to simple textual sorting of the lines of the annotated candidate stream according to the violation vector column that comes last in each line. Since, in addition to the intrinsic sorting order between the two types of marks, shorter column entries are sorted before longer ones and individual constraint violation fields in the violation vector are always formally separated by the non-violation mark ', using sorting as the device to effect minimal violation or optimization is sound. The sorted output of 'sort' can then e.g. be stored to a file, viewed directly on the screen or fed into a graphical tree display tool for convenience, with the first candidate line showing the optimal output.

After this tour-de-force through the general architecture of OT SIMPLE, let us now proceed to describe how one can fill both GEN and CON with substantive content, provide some input and then see OT at work using this software tool.

[8]This equivalence was also alluded to in Prince and Smolensky (1993, p. 19).

[9]With $*$ = ASCII code 42_{10} and ' = ASCII code 39_{10}, the noted sorting order follows.

3 Specifying GEN

GEN is the component of OT that is responsible for structural enrichment of a bare input. The immediate question is therefore how to specify the space of structural possibilities. In OT SIMPLE a context-free phrase structure rule format is used for this purpose. This degree of formal power should suffice even for some cases of syntax modelling. As is well-known, context-free grammars (CFGs) can only describe tree structures, which is therefore a limitation that OT SIMPLE currently inherits (cf. Tesar 1996 for the same assumption). While more general reentrant graph structures may be desirable for some multiply-linked structures as used e.g. in autosegmental representations, we will see later that their present omission is not significant for the important class of automatic, i.e. predictable sharing or linking. (2) presents a particularly simple example, the first part of a GEN grammar[10] file `hessian.gen`, which will be extended later. Note that the `.gen` file name extension is obligatory. We hasten to add that OT SIMPLE, like the overall OT *framework* itself, is entirely neutral with respect to the substantive constituent and rule inventory that a theorist may wish to adopt in specifying the desired space of possible GEN structures.

(2) SAMPLE GEN GRAMMAR

```
startsymbol word.                               % 0
word ---> ft.                                   % 1
word ---> ft, ft.                               % 2
                                                % 3
ft   ---> syl.                                  % 4
ft   ---> syl, syl.                             % 5
                                                % 6
syl  ---> m.                                    % 7
syl  ---> 'Rt', m.                              % 8
syl  ---> 'Rt', m, m.                           % 9
syl  ---> 'Rt', m, m, 'Rt'.                     % 10
                                                % 11
m    ---> 'Rt'.                                 % 12
                                                % 13
'Rt' ---> [].                                   % 14
```

[10] This term is used interchangeably with 'GEN structur(e/al) grammar' in what follows. It is equivalent to Tesar (1996)'s 'position structure grammar'.

```
                                                      % 15
a # 'Rt' ---> "SONORANT", "DORSAL".                   % 16
t # 'Rt' ---> "SPREAD_GLOTTIS", "CORONAL".            % 17
```

The context-free productions in lines 1-5 define expansions of word, foot (`ft`) and syllable (`syl`) into their maximally binary lower constituents in the familiar prosodic hierarchy, whereas subsyllabic structure receives a moraic treatment in lines 7-10, with a minimum of one mora (`m`) and a maximally bimoraic structure with one additional onset-position root node (`'Rt'`) and one extra coda position (line 10). Moras also dominate root nodes (line 12). The first device in this CFG format that is special to OT appears in line 14. It specifies a production rule that rewrites into a built-in `[]` terminal symbol equivalent in function to OT's empty structure symbol, $\Box$. Note that it is under complete control of the GEN grammar writer which parts of the structure should be eligible for free $\Box$insertion. Lines 16 and 17, which specify alternative, non-empty expansions of root nodes illustrate two more notational devices: first, terminal symbols like the privative features `SONORANT, DORSAL, SPREAD_GLOTTIS, CORONAL` are distinguished from nonterminals by surrounding double quotes. More importantly, arbitrary productions can be labelled with a symbol in front of the hash sign (`#`); thus, e.g. `a` acts as a shorthand reference label for the rule in line 16. Since rules in turn are in familiar correspondence with local trees, labels can be understood as triggering the presence of local trees in candidates. Labels are the sole means to specify inputs. As we will see later in concrete GEN usage, inputs in OT SIMPLE are nothing other than a comma-separated list of such labels enclosed by square brackets, e.g. `[t,a]`.

Any CFG by definition must specify a distinguished start symbol. If, unlike line 0 in (2), no overt `startsymbol YourStartSymbol.` declaration is included, the startsymbol `word` is assumed by default. For those who are less familiar with the Prolog naming and file layout conventions that are also used in the GEN grammar file format, it may be worth emphasizing that each rule must be terminated with a period symbol, that the arrow must consist of exactly three consecutive minus signs followed by a greater-than symbol, and that symbols with upper-case initials must be enclosed in single quotes. Otherwise, the GEN grammar can be written in free format with arbitrary numbers of whitespace characters between symbols, and rules may appear in any order. Moreover, the rest of the line after a percent sign is ignored and may contain comments.

In order to satisfy the 'Freedom of Analysis' condition, a good GEN structural grammar must be highly ambiguous. This property is obtained in (2), which allows a large number of alternative structures to be built from terminal input seeds such as `[t,a]`. In (2), all categories except for `m`(ora) have more than one expansion, and with the help of free epenthesis quite baroque tree structures will be realizable. One important additional OT concept that is not directly visible in a GEN grammar, however, is *underparsing*. The reason for its invisibility is that in OT SIMPLE underparsing is built-in: it automatically pertains to all lefthand-side categories of labelled rules that can be used as input, e.g. `'Rt'` in (2). This means that the set of different structural realizations w.r.t. the GEN grammar will be multiplied with all possible underparsings of input tokens used in the tree structures.

Another point to be taken into account is the cardinality of the GEN set in conjunction with the amount of freely insertible empty structure. While not being the case for the rules in (2), in OT SIMPLE GEN structural grammars are generally allowed to contain recursive productions. If, in keeping with the original presentation of OT, candidate structures are actually enumerated one at a time, some means must be found to ensure GEN termination. Especially with an infinite supply of empty symbols GEN enumeration might otherwise never halt. Since for all practical purposes a finite GEN set appears quite tolerable, OT SIMPLE consciously opts for incompleteness here by treating a finite but arbitrarily large number of empty symbols as an additional, but invisible kind of technical input. This upper bound on the number of epenthetic elements must be specified by the user. Hence the sum of GEN's input proper and this technical input is also finite, and if the GEN grammar contains no direct or indirect *left*-recursion,[11] the entire set of candidates will be always finite. Finiteness of the GEN set also is a necessary precondition for the implementation of EVAL in OT SIMPLE, which, we recall, is modelled by sorting. While, as already noted, infinite GEN sets are not a problem for Ellison's approach, the inspection of infinite set descriptions themselves can be uninstructive. Individual candidates, in contrast, are more easily understood; with them we firmly reside on the object rather than on the description level. Since we know of no analyses which crucially depend on infinite GEN sets, one need not be overly bothered by this small restriction.

[11] The ban on left-recursion is due to the particularly simple depth-first, left-to-right rule application strategy which in turn straightforwardly follows from Prolog's internal proof strategy. Note that right-recursive rules *are* admitted. However, we know that every context-free language which does not include the empty string can be described by a CFG without unit productions or general left-recursion (a corollary of the Greibach normal form theorem), hence in principle this situation is always avoidable. Because the necessary grammar transformations may change parse trees, however, it might be desirable to provide for alternative tree traversal strategies directly. This is left for future improvements.

This concludes our discussion of GEN grammar specification. We will provide specific details of how GEN is actually implemented in section 7.1, and show the concrete GEN user interface in section 5.

4 Specifying constraints

Constraints in OT SIMPLE act to annotate candidates with violation vectors. Each column of the vector in turn consists of a contiguous string of asterisks corresponding to actual violations or a single quote for non-violation. Constraints operate on the flattened tree format that is output by GEN for purposes of textual representation, containing one candidate tree per line of GEN output. While this is shown in more detail in section 5, here are some typical candidates for immediate illustration:[12]

(3) TYPICAL CANDIDATES

```
word(ft(syl(Rt(SPREAD_GLOTTIS,CORONAL),m(Rt(SONORANT,DORSAL))))).
word(ft(syl(Rt(SPREAD_GLOTTIS,CORONAL),m({Rt(SONORANT,DORSAL)})))).
word(ft(syl(Rt([]),m({Rt(SPREAD_GLOTTIS,CORONAL)}),\
    m({Rt(SONORANT,DORSAL)})))).
```

What matters for present purposes is the candidate format and not its content. In this format a local tree with mother node M and daughters $D_1 \ldots D_n$, generated by the corresponding rule `M ---> D1, ... DN.`, is formatted as `M(`D_1, ..., D_n`)`. Daughters may again be local trees or, alternatively, terminal symbols "T_i", the latter being simply formatted as T_i. Curly braces, denoting underparsing, may surround local trees.

Now, in general a constraint first reads in each candidate line and stores an intermediate copy of the line in a buffer. It then looks for occurrences of patterns that indicate constraint violation. The offending pattern is substituted by asterisks, either directly or through a cascade of intermediate substitutions. The latter option often turns out to be a helpful *divide-and-conquer*-type strategy to attack the problem at hand. Then all other material is deleted. The result constitutes a new column field in the violation vector column under construction, with the position of the field textually corresponding to the constraint's rank order, as is familiar from the usual tableau layout. Appending the partial violation vector just constructed to

[12] Here and in the following, overlong candidate lines will be folded for presentational purposes, as indicated by the backslash.

the previously saved copy of the candidate restores a complete candidate-plus-partial-annotation line, thereby giving the next constraint in the rank order a chance as well. This procedure is repeated for every candidate line from the GEN output.

The central question now is how to specify substitutions and which mechanism to use for actually carrying out these pattern replacements. A well-known efficient device for pattern substitution in linear time is a *finite-state transducer* (FST). FSTs have well-understood mathematical properties. In particular, they are closed under composition, which means that for an arbitrary cascade of FSTs one can always find another single FST that is completely equivalent in its behaviour. The patterns that can be mapped via FSTs to other patterns must be specifiable by a *regular expression*. In OT SIMPLE Constraints-as-FSTs are specified in the format accepted by 'sed', a standard software tool that comes with the system software of at least all UNIX OSes. 'sed' is a stream editor which can *inter alia* perform pattern substitutions in the line-by-line manner outlined above. In OT SIMPLE, then, a constraint is made of a sequence of 'sed' actions and stored in a 'sed' script file.

The following is one the most simple constraints, *STRUC 'Avoid structure' (cf. Prince and Smolensky 1993, ch.3,fn.13). In the formalization we adopt here it emits a violation mark for every immediate domination relationship in the tree. It follows that *STRUC is an example of a binary constraint. Luckily, in the flattened tree format described above there is a single-character symbol indicating immediate domination in a local tree, the opening round bracket. This being said, let us look at the actual, unedited formulation of the constraint below (note that empty and hash sign-initial lines, the latter containing comments, are ignored by 'sed'):

(4) *STRUC

```
# COMMON CONSTRAINT PROLOGUE
# save candidate to buffer

h

# delete violation vector (everything following the dot)
# to get pure candidate

s/\..*//g

# CONSTRAINT-SPECIFIC MAIN PART
```

```
# delete everything except structural dominance symbol (

s/[^(]//g

# substitute ( by *

s/(/\*/g

# COMMON CONSTRAINT EPILOGUE
# remove all non-violation star material

s/[^\*]//g

# append violation stars after candidate (creates newline)

x;G

# convert superfluous newline into constraint separator character '

s/\n/\'/
```

Apart from the commands to save a copy of the current line (h), exchange the current line buffer and the save buffer (x) and append the saved copy after the current line (G), all other actions are substitution specifications. Substitution commands will form the core of all constraint specifications in this paper. Their concrete syntax is `s/Pattern/Replacement/g`. Note that the trailing `g` indicates that substitutions are to be made for every occurrence of Pattern in the line, not just the first (for the latter option, omit the `g`). Space precludes a full explanation of the syntax of admissible Pattern and Replacement expressions, for which see e.g. Gulbins (1988, p.319-24), but in order to understand the constraint script in (4) and others to follow, let us note a few salient points here.

While simple strings are typed in as such, the empty string denoting deletion of the pattern is marked by a missing Replacement specification, i.e. the second and third slashes are adjacent. If any of a whole set of characters should match against a single character in the line, the set may be enumerated between square brackets `[]`. An initial circumflex `^` acts as a complement operator, i.e. with it a character is matched that is *not* in the set of characters to follow. Some symbols including the asterisk, the dollar sign and – in some contexts – also the round and square brackets have predefined meaning for 'sed'. If these must be matched literally, a preceding backslash is provided as an escape character in order to turn off the predefined meaning. One important predefined operator is the Kleene star operator, written as an asterisk symbol. It is used for specifying an unbounded number of concatenations (including zero concatenation) of the character expression preceding it. The predefined dollar symbol is also sometimes helpful, as it only matches the end of the line. Finally, in deviance from the escape convention, `\n` matches the newline character.

Since making the initial candidate copy and deleting old violation stars will always form the prologue of any constraint script, and deleting non-asterisk material, restoring the copy and substituting the superfluous newline character by a single quote always forms the epilogue, we shall omit both of these parts in the text from now on. Their purpose is clear: provide a fresh start for each constraint in the beginning and guarantee a well-defined evaluation result at the end. In particular, an unviolated constraint issues a single single quote character, whereas a constraint that is violated N times emits a single quote followed by a contiguous string of $N > 0$ asterisks.

In (5) and (6) the faithfulness constraints FILL and PARSE$_{Seg}$ are displayed, which penalize epenthetic structure and segmental underparsing, respectively. Unsurprisingly, they can be implemented as simple variants of $*$STRUC, as the opening square and curly brackets similarly indicate the presence of empty elements and underparsed input.[13]

(5) FILL

```
# delete everything except epenthesis symbol [

s/[^\[]//g

# substitute [ by *

s/\[/\*/g
```

(6) PARSE$_{Seg}$

```
# delete everything except underparse symbol {

s/[^{]//g
```

[13] This constraint family relationship was already hinted at in McCarthy and Prince (1993, fn.16).

```
# substitute { by *

s/{/\*/g
```

A final remark: since constraints can become much more complex than this, it is not only good style but almost vital for later constraint maintenance to include a comment before each 'sed' action.

5 OT at work

It is time to put the pieces together and run through a very simple example. Suppose we have prepared a correct GEN grammar file `hessian.gen` containing the material in (2), and also stored the above three constraints into script files `NO-STRUC, FILL, PARSE-SEG`. Then we are ready to start experimenting with OT SIMPLE. In the following, the OS command interpreter prompt is displayed as a dollar sign followed by a number, user keyboard input is in sans serif typeface, and OT SIMPLE's response is in `typewriter` font. Witness the following interaction to just generate the unevaluated candidate set from a simple input [t,a] with a maximum of 2 epenthetic positions. The command GEN is provided by OT SIMPLE, and its arguments must be enclosed in double quotes, as shown.

(7) GEN AT WORK

```
$1 GEN "hessian, [t,a], 2"

word(ft(syl(Rt(SPREAD_GLOTTIS,CORONAL),m(Rt(SONORANT,DORSAL))))).
word(ft(syl(m(Rt(SPREAD_GLOTTIS,CORONAL))),syl(m(Rt(SONORANT,DORSAL))))).
word(ft(syl(m(Rt(SPREAD_GLOTTIS,CORONAL)))),ft(syl(m(Rt(SONORANT,DORSAL))))).
word(ft(syl(Rt(SPREAD_GLOTTIS,CORONAL),m({Rt(SONORANT,DORSAL)})))).
...
word(ft(syl(Rt([]),m({Rt(SPREAD_GLOTTIS,CORONAL)})),syl(m(Rt([])))),\
    ft(syl(m({Rt(SONORANT,DORSAL)})))).
word(ft(syl(Rt([]),m(Rt([]))),syl(m({Rt(SPREAD_GLOTTIS,CORONAL)}))),\
    ft(syl(m({Rt(SONORANT,DORSAL)})))).
$2
```

This small example actually generates 432 candidates! Shown are the first four candidates and the last two, in generation order. After the first candidate displaying some reasonable structural assignment, i.e. a single foot dominating a single syllable with /t/ in onset and /a/ dominated by a mora, things start getting weirder, with two syllables and two feet being the next two possibilities. Then comes the first candidate again, but with underparsed /a/ as indicated by curly brackets around the root node subtree `{Rt(SONORANT,DORSAL)}`.[14] The final two candidates all exhaust the maximum limit of two epenthetic elements `[]`, incorporated into different positions of bizarre two-feet-three-syllable structures with both input segments being underparsed.

Let us move on to some constraint action. Here is the result of plugging in CON with two constraints, $\textsc{Parse}_{seg}$ and $*\textsc{Struc}$. Note the use of the predefined command CON, which takes a list of constraint files in ranking order as arguments. As usual, individual OT components which stand in a feeding relationship are connected via pipes |. Two auxiliary commands provide some additional convenience. COUNT augments the candidate display with line counts and reformats the candidate line to display the violation vector below each candidate for a more compact presentation. SHOW_PAGEWISE provides a service for viewing the candidate stream one screen page at a time (pressing the space bar displays the next page).

(8) GEN PLUS CON IN ACTION

```
$3 GEN "hessian, [t,a], 2" | CON PARSE-SEG NO-STRUC | COUNT | SHOW_PAGEWISE


1
word(ft(syl(Rt(SPREAD_GLOTTIS,CORONAL),m(Rt(SONORANT,DORSAL)))))
''******
2
word(ft(syl(m(Rt(SPREAD_GLOTTIS,CORONAL))),syl(m(Rt(SONORANT,DORSAL)))))
''********
3
word(ft(syl(m(Rt(SPREAD_GLOTTIS,CORONAL)))),ft(syl(m(Rt(SONORANT,DORSAL)))))
''*********
4
word(ft(syl(Rt(SPREAD_GLOTTIS,CORONAL),m({Rt(SONORANT,DORSAL)}))))
'*'******
...
```

Note that candidates 1-3 only display increasing amounts of $*\textsc{Struc}$ violations, whereas candidate 4 is the first to incur a single $\textsc{Parse}_{seg}$ violation due to /a/ underparsing.

[14] The particulars of the (segmental) feature theory assumed here are immaterial to the present discussion. Underparsing on the level of root nodes stems from specifying root node rules `SomeLabel # 'Rt' ---> ...` as bearing the input labels in the GEN grammar. With a different GEN grammar, the level at which underparsing occurs can of course be changed at will.

Finally, sticking in two more predefined commands, EVAL, for candidate sorting in increasing violation order, and TREE, a graphical tree display command operating on the topmost line, we have assembled all that is necessary to display the optimal candidate:

(9) COMPUTING THE OPTIMAL OUTPUT FOR /ta/

```
$4 GEN "hessian, [t,a], 2" | CON PARSE-SEG NO-STRUC | EVAL | TREE
```

```
                           word
                            |
                            .
                            |
                            ft
                            |
                            .
                            |
                           syl
                            |
                 .---------------------.
                 |                     |
                 rt                    m
                 |                     |
            .-----------.              .
            |           |              |
    spread_glottis   coronal           rt
                                       |
                                  .--------.
                                  |        |
                              sonorant   dorsal
```

The result is as expected: monosyllabic /ta/ as the winning candidate is minimally structured and contains no underparsed segments.

In the next section we move on to something more serious, the task of formalizing and implementing a real analysis that has been published. This case study serves to illustrate the practical utility of OT SIMPLE, while also showing important additional constraint coding techniques.

6 Formalizing Golston & Wiese (1996)

Golston and Wiese (1996) investigate what looks like a case of subtractive plural morphology in Hessian German, illustrated in (10).

(10)

Singular	Plural	
hɔnd̥	hɔn	'dog'
dɔg̥	dɔː	'day'
bɛrg	bɛr	'mountain'

The authors develop an optimality-theoretic analysis on the basis of a broad range of data including the items we have just seen, arguing that the dialects of Hessian versus Standard German differ only in terms of constraint ranking. Furthermore, they are able to dispense with the assumption of a morphologically distinctive process of truncation for the phenomenon at hand. In the following, let us provide a very brief summary of the essentials of their analysis. The reader is urged to consult the original paper for additional detail.

6.1 The analysis of Hessian subtractive plural

Golston & Wiese note that, over and above the usual *-er,-n,-e,* -∅ plurals also found in Standard German, Hessian has subtractive plurals. They summarize the conditions under which subtraction occurs as follows: subtraction if the stem ends in /ln, nd, ŋg, ʀg, Vg/. Hence, after omitting the last segment in these sequences, such plurals end in a sonorant. This observation makes some sense cross-dialectally, since in Standard German plural nouns invariably end in an unstressed sonorant-final (/ə,l,ʁ,n/) syllable. Importantly, in Hessian -∅ plural is in complementary distribution with subtractive plural, the former occurring if the stem does *not* end in /ln, nd, ŋg, ʀg, Vg/. The authors uncover the generalization that subtractive plurals can only be formed if no distinctive feature is lost in the process. Since they assume that adjacent identical features within a morpheme are shared, stems such as *hɔnd, dɔg* are analyzed with shared final coronal and dorsal features respectively. Last segment subtraction delinks only one of the linked segments, hence preserving the feature as a whole. Unlike these cases, stems such as *flek* 'patch', *hɛls* '(no gloss)', *ʃvɛnts* '(no gloss)' have unshared final laryngeal and manner features (spread_glottis and continuant) under the featural classification scheme of Golston & Wiese (see (11) below for a replication of this scheme in OT SIMPLE's format).

Their constraint-based account of subtractive pluralization then boils down to the following: Hessian plurals end in a sonorant, to be captured by a constraint SON]PL.[15] SON]PL must hold except when compliance with it would invoke epenthesis or underparsing of distinctive features. This motivates additional constraints FILL and PARSE-FEATURE ranked above SON]PL. The fact that segments are sometimes deleted in order to respect SON]PL means that another constraint PARSE-SEG must be ranked below it. Segment-level underparsing unsurprisingly is the way to achieve subtractive plurals, so familiar PARSE-SEG ensures that underparsing will be minimal.

[15] See the original paper for an argument why SON]PL is not a language-particular constraint.

6.2 Implementing the analysis

6.2.1 Extending GEN

A necessary ingredient of any implemented OT analysis is to get GEN to produce the correct and all-inclusive range of structures for a given input. To that end, let us extend the GEN structural grammar given earlier under (2). While the authors did not commit themselves to a specific theory of prosodic structuring, taking over the particular treatment in terms of feet, moras and root nodes from (2) is wellfounded. The simple reason why we can adopt this part of the GEN grammar in unmodified form without fear of distorting their analysis is that no constraint used by Golston & Wiese is sensitive to prosodic structure. In lines 16 and 17 of (2), then, we have already seen examples of the general format in which input-labelled rules for segmental definitions can be specified. Extending the segmental definitions beyond the two definitions for `t,a`, we now simply copy the distinctive feature chart of Golston & Wiese into the same rule format. This yields the addendum to `hessian.gen` depicted below:

(11)

```
'O' # 'Rt' ---> "SONORANT", "DORSAL".                      %16
i   # 'Rt' ---> "SONORANT", "DORSAL".                      %17
'E' # 'Rt' ---> "SONORANT", "DORSAL".                      %18
u   # 'Rt' ---> "SONORANT", "DORSAL".                      %19
o   # 'Rt' ---> "SONORANT", "DORSAL".                      %20
                                                           %21
b   # 'Rt' ---> "LABIAL".                                  %22
p   # 'Rt' ---> "SPREAD_GLOTTIS", "LABIAL".                %23
                                                           %24
d   # 'Rt' ---> "CORONAL".                                 %25
t   # 'Rt' ---> "SPREAD_GLOTTIS", "CORONAL".               %26
                                                           %27
g   # 'Rt' ---> "DORSAL".                                  %28
k   # 'Rt' ---> "SPREAD_GLOTTIS", "DORSAL".                %29
                                                           %30
s   # 'Rt' ---> "CONT", "SPREAD_GLOTTIS", "CORONAL".       %31
'S' # 'Rt' ---> "CONT", "SPREAD_GLOTTIS", "CORONAL".       %32
                                                           %33
n   # 'Rt' ---> "SONORANT", "NASAL", "CORONAL".            %34
m   # 'Rt' ---> "SONORANT", "NASAL", "LABIAL".             %35
'N' # 'Rt' ---> "SONORANT", "NASAL", "DORSAL".             %36
                                                           %37
l   # 'Rt' ---> "SONORANT", "CORONAL".                     %38
                                                           %39
r   # 'Rt' ---> "SONORANT", "DORSAL".                      %40
                                                           %41
h   # 'Rt' ---> "SPREAD_GLOTTIS".                          %42
```

Note, first of all, that due to restrictions in the machine representation of IPA characters, IPA /ɔ,ɛ,ʃ,ŋ/ appear as `'O','E','S','N'`. Furthermore, definitions for vowels lack distinctive place, as this was not given in Golston & Wiese's analysis, presumably because it is immaterial to plural formation itself. In the same vein, definitions for `'S',m,'N',r,h` were merely inferred by analogy. With epenthesis and underparsing already provided by earlier parts of the GEN grammar and the underlying GEN mechanism, respectively, specification of GEN is essentially complete. Producing a candidate set for, say, *hɔnd* 'dog', then will be as simple as GEN "hessian, [h,'O',n,d], 1".

6.2.2 The constraint Son]pl

As a matter of fact, three of the five constraints needed to model Golston & Wiese's analysis are already in place: Parse$_{Seg}$ and Fill were defined earlier. The same goes for ∗Struc, which did not appear in the original analysis, but is entirely compatible with it and surely a necessary move to minimize unmotivated prosodic structure.

The remaining two constraints are Parse-Feat and Son]pl. They are more difficult to implement than the other ones we have seen. However, it turns out that they are also quite instructive examples of important constraint specification strategies that will be of general use in a regular transduction-based constraint language.

Below comes Son]pl. We continue with our practice of leaving out both the preparatory prologue and the cleaning-up actions of the epilogue, both of which were previously identified as common to all constraints. Also, since the extra morphological restriction to plural is obviously redundant in the context of our focussed task of deriving only plurals, we refrain from introducing additional complexity in GEN grammar, input specification and this constraint, therefore omitting all actual reference to plural in the implementation (as in Golston & Wiese's paper). The reader is encouraged to implement plural conditioning as an exercise.

(12) Son]pl

```
# delete uninteresting symbols

s/word//g;s/ft//g;s/syl//g;s/m//g;s/[\(\)]//g;s/[]\[]//g
s/CORONAL//g;s/NASAL//g;s/CONT//g;s/SPREAD_GLOTTIS//g
s/LABIAL//g;s/DORSAL//g;s/,//g
```

```
# start classifying four parsing states ...
#  substitute underparsed sonorant by 1

s/{RtSONORANT}/1/g

# substitute parsed sonorant by 2

s/RtSONORANT/2/g

#  substitute underparsed non-sonorant by 3

s/{Rt}/3/g

#  substitute parsed non-sonorant by 4

s/Rt/4/g

# remove all underparsed segments, since interest here
# is on PARSED sonorants

s/[13]//g

# insert speculative violation mark for word end $
# Reason: we want totally underparsed words to violate
# the constraint as well!

s/$/\*/g

# revoke speculative violation mark * at right word
# edge if preceded by parsed sonorant 2

s/2\*//g
```

As is typical for many constraints, SON]PL is only interested in certain narrowly-defined configurations involving the feature SONORANT. Therefore, an initial step in (12) consists of deleting all those uninteresting symbols that also populate the candidate tree, in effect bringing the interesting ones closer together. Note that in the absence of formal means to form a complement set to a given set of interesting strings, an operation which is unfortunately not available in the restricted inventory of regular expression operators that 'sed' implements, we must define the set of deletable symbols by piecewise enumeration. This introduces a certain amount of unnecessary interdependency between constraint formulation and GEN specification, since quite general constraints that could otherwise be reused with different GEN structural grammars here must depend on a detailed knowledge of GEN.

The next step illustrates another general technique: for the problem at hand, identify a partitioning into meaningful equivalence classes and substitute tokens of each of the classes by a canonical representative, e.g. an otherwise unused natural number. While not strictly needed from a formal point of view, substituting possibly complex tree configurations by short representatives certainly helps to keep constraint formulation manageable for humans. Here our problem is how to identify parsed sonorants at the right word edge. This induces a natural 2 x 2 partition with respect to the binary dimensions *parsed* vs *underparsed* and *sonorant* vs *non-sonorant*. Since underparsing itself was earlier defined to occur at the root node level, we find expressions like `s/{Rt}/3/g`, which state that an underparsed non-sonorant (curly brackets plus root node symbol plus absence of the string `SONORANT`) is to be substituted by `3` wherever it occurs in the entire candidate representation.

Now, to understand the logic of the following lines it helps to consider the underparsing options in a bit more detail. If there is an unbroken chain of final underparsed segments preceded by a parsed segment, that segment would be final in terms of actual pronunciation, since phonetic interpretation is deemed to disregard underparsed structure. Its substantive content – sonoranthood or not – could then be used to decide whether to output a violation mark or not. However, a special case arises for totally underparsed input, the so-called 'null parse' of Prince and Smolensky (1993), where there is no such left-over segment. Choosing the behaviour that seems to be most conformant with the text analysis of Hessian, let us assume that SON]PL is violated in this case. To correctly implement the constraint, it is therefore best to proceed in an inverse fashion: stipulate a violation and revoke it when the only positive configuration, namely a parsed word-final sonorant, is met.

In general, this 'inverse' constraint coding strategy is best used when enumerating all violating configurations would be cumbersome, but describing the non-violating case is comparably easy. Towards this end we remove the underparsed segments, both to find the actual word end and also because they do not contribute to our sought-after positive configuration. Then the single stipulated violation mark is inserted by transducing from the word end symbol that is invisibly contained in any line of text according to 'sed'. Since there will be no other source of violation stars for this constraint, SON]PL is hereby classified as a binary constraint, which is in accordance with the published analysis although the authors do not overtly say so. If it was there in the candidate in the first place, we now have the desired locally detectable context, namely a parsed-sonorant symbol `2` left-adjacent to the unique word-final violation symbol, which we now delete. All other configurations including the 'null parse' do not meet this context, hence the violation mark stays.

6.2.3 The constraint PARSE-FEAT

The second constraint, PARSE-FEAT, shares some similarities with the one we have just seen, but introduces additional interesting complexities that are well-worth discussing. As it turns out, for purposes of implementation it makes life easier to understand PARSE-FEAT as a constraint *schema*, which is expanded into a concrete constraint for each feature (cf. also Wiltshire 1994, Kiparsky 1994). What is therefore shown below is one concrete variant, PARSE-CORONAL, which may serve as a recipe for all other incarnations of the schema. A second point worth noting is that, at least for the analysis at hand, we can view feature-level underparsing to follow from segment-level underparsing. This asymmetric dependency trivially holds for isolated features of a given underparsed segment, features that are absent from adjacent segments. However, we will see that with appropriate simulation of automatic sharing of adjacent features in the constraint itself we can also reduce featural underparsing of shared instances to segmental underparsing. Hence, the assumption of segment-level underparsing, as specified in the current GEN structural grammar, need not be revisited in what follows. Here then comes the formal implementation of PARSE-CORONAL:

(13) PARSE-CORONAL

```
# delete uninteresting symbols

s/word//g;s/ft//g;s/syl//g;s/m//g;s/[\(\)]//g;s/[]\[]//g
s/SONORANT//g;s/NASAL//g;s/CONT//g;s/SPREAD_GLOTTIS//g
s/LABIAL//g;s/DORSAL//g;s/,//g

# start identifying four parsing states ...
#  substitute underparsed coronal by 1

s/{RtCORONAL}/1/g

#  substitute parsed coronal by 2

s/RtCORONAL/2/g

#  substitute underparsed non-coronal by 3

s/{Rt}/3/g
```

```
#  substitute parsed non-coronal by 4

s/Rt/4/g

# collapse adjacent 1...1 to 1
# (reduce chain of underparsed coronals)

s/11*/1/g

# collapse adjacent 2...2 to 2
# (effects automatic sharing of parsed coronals)

s/22*/2/g

# remove ‘protected’ instances of underparsed coronals, i.e.
# adjacent to parsed coronals...
#  parsed before underparsed order

s/21//g

#  underparsed before parsed order

s/12//g

# all remaining un’protected’ underparsed coronals
# indicate constraint viol.

s/1/*/g
```

The upper portion of the constraint specification is by now familiar: again, we see the removal of uninteresting symbols followed by a four-way classification, this time relating to coronals. Only half of the four classes are actually needed in the following, but we stick to the general recipe for expository reasons.

The next stage is more interesting, as it shows the promised technique for implementing cases of automatic, non-distinctive sharing in the constraint itself, rather than having it already present in the candidate. Recall that local sharing of features was a key ingredient of Golston & Wiese's analysis, forcing a need to reconcile this demand with the tree structure limitation of candidates in OT SIMPLE. Enriching the GEN implementation to cater for graph-structured output invokes all sorts of questions relating to a suitable flat representation of graphs that the constraints would be happy with, questions we would like to put aside for the moment. Luckily, these questions do not arise for automatic sharing under locality. The idea is this: Whenever we have a contiguous chain of same-state features, e.g. three parsed coronals in a row, we collapse the chain into a single representative. This move then literally captures the essential aspect of automatic sharing that we need here, namely that each shared feature counts as only one instance on its tier.

Now we are ready to identify distinctive feature losses. Note that under the intended behaviour of PARSE-FEATURE demanded by Golston & Wiese's analysis we cannot simply identify underparsed coronals with constraint violations. If underparsed coronal segments are adjacent to a *parsed* coronal segment, this corresponds to a scenario where at least one surviving association line would still extend from the parsed segment on the root node tier to the coronal tier, thereby 'protecting' the coronal feature. Therefore, such 'protected' contexts do not count towards a violation, and we need to delete them in order to properly isolate the focal cases of unprotected underparsed coronals surrounded by non-coronals. These cases are then put into a one-to-one relationship with violation marks, as expressed by the last line shown in (13). Again, the epilogue not shown here deletes all non-asterisk material, thereby including leftover instances of the classificatory numbers 2...4.

6.2.4 Running the analysis

Having removed the last roadblock to an implemented version of Golston and Wiese (1996), let us put together the individual pieces to show a full OT SIMPLE computation for the plural of *hɔnd* 'dog':

(14) COMPUTING THE PLURAL

```
$5 GEN "hessian, [h,'O',n,d], 1" | \
CON PARSE-FEAT FILL SON]PL PARSE-SEG NO-STRUC | EVAL | TREE
```

(14) states that GEN should generate output corresponding to *hɔnd* with at most 1 epenthetic element. The output is fed (|) into the constraint stage CON. CON takes the constraint file names as argument, and delivers the concatenation of the constraint scripts to 'sed' for execution. The violation-annotated output of this stage is then fed to EVAL, which sorts the violation vectors. Finally, TREE picks the topmost-sorted winning candidate and displays it in tree form. Here is this result, the plural of *hɔnd* as actually output by OT SIMPLE:

(15) The Winning Plural Candidate: /hɔn<d>/

```
                               word
                                 |
                                 .
                                 |
                                ft
                                 |
                                 .
                                 |
                                syl
                                 |
       .----------------.---------------------.----------------.
       |                |                     |                |
      rt                m                     m               {}
       |                |                     |                |
       .                .                     .                .
       |                |                     |                |
spread_glottis         rt                    rt               rt
                        |                     |                |
                    .--------.        .-------.-------.        .
                    |        |        |       |       |        |
                sonorant  dorsal  sonorant  nasal  coronal  coronal
```

Note that the curly brackets which delimitated the underparsed structure in the flat textual candidate representation reappear as a designated tree node `{}`.[16] The following is an excerpt from the full tableau containing the winner. It shows the first three most harmonic candidates and the least harmonic candidate, out of 2144 candidate lines and in the order delivered by OT SIMPLE.[17]

[16]This behaviour is due to Prolog, the programming language used for GEN and TREE: its surface syntax allows a convenient circumfix notation for curly brackets, in order to visibly group together a possibly complex Prolog term. However, this is just syntactic sugar for a unary functor symbol {}. Since the tree output of general Prolog terms by TREE displays each functor as a tree node and uses vertical arcs to indicate term embedding, the picture follows.

[17]Actually, under the present GEN grammar there are four candidates that tie for least harmony, since the epenthetic element can be moraic or not and start a new foot or not. Both of these dimensions are not subject to extra differentiating constraints in the analysis that serves as our running example. When candidates have the same harmony, their textual order as output by GEN is left unchanged by EVAL/'sort', which behaviour classifies it as a *stable* sort.

(16) Annotated Candidate Set for the Plural

```
1
word(ft(syl(Rt(SPREAD_GLOTTIS),m(Rt(SONORANT,DORSAL)),\
    m(Rt(SONORANT,NASAL,CORONAL)),{Rt(CORONAL)})))
''''*'*********
2
word(ft(syl(Rt(SPREAD_GLOTTIS),m(Rt(SONORANT,DORSAL))),\
    syl(Rt(SONORANT,NASAL,CORONAL),m({Rt(CORONAL)}))))
''''*'**********
3
word(ft(syl(Rt(SPREAD_GLOTTIS),m(Rt(SONORANT,DORSAL)))),\
    ft(syl(Rt(SONORANT,NASAL,CORONAL),m({Rt(CORONAL)}))))
''''*'***********
...
2144
word(ft(syl({Rt(SPREAD_GLOTTIS)},m({Rt(SONORANT,DORSAL)})),\
    syl(m({Rt(SONORANT,NASAL,CORONAL)}))),ft(syl(m(Rt([]))),syl(m({Rt(CORONAL)}))))
'**'*'*'****'****************
```

The topmost candidates incur just one PARSE-SEG violation, but differ in their amount of structure as counted by NO-STRUC (9-11 violations). In contrast, the least harmonic candidate has 16 NO-STRUC violations, all four segments underparsed, violates SON]PL and FILL once each, and contains two instances of (coronal) PARSE-FEAT violation. Note that the last violation count is explained by the epenthetic element that intervenes between coronal /n/ and /d/, thus removing the adjacency required for automatic feature sharing under the current formalization of PARSE-FEAT.

It is easy to see how, using OT SIMPLE, one could now go on to experiment with different rankings by simply changing the order of CON arguments, or single out specific constraints to observe their action in isolation, or use a selected subset of salient candidates previously stored in a file to speed up human inspection for purposes of constraint debugging etc.

One such case where quickly running an experiment with OT SIMPLE has helped to uncover an important hidden assumption of Golston and Wiese (1996) is the behaviour of Standard High German *hʊnd* 'dog' under pluralization, which the authors claim should be obtainable from simply reranking Fill below Son]pl and Parse-Seg. Surprisingly, however, we get the same output as for Upper Hessian instead of the expected grammatical output *hʊndə*, with final schwa epenthesis. A moment's reflection resolves the puzzle: the epenthetic final element inserted by OT SIMPLE is devoid of featural content, contrary to the tableau notation (`[E]`) and wording ('epenthetic vowel') of Golston & Wiese. Therefore Son]pl cannot be satisfied. The small point to be made here is that simply running the experiment in OT SIMPLE was sufficient to point to the crucial nature of the assumption of contentful epenthesis, something the authors did not note *expressis verbis*. To remedy this defect in OT SIMPLE in a principled manner, we will provide a suitable GEN facility to specify featural content for epenthetic elements in the future. Meanwhile, a quick fix would resort to enriching SON]PL by an additional initial transduction step `s/\[]/SONORANT/g`, thereby simulating epenthetic sonoranthood on-the-fly.

Summing up then, having a software tool such as OT SIMPLE can be an effective means to uncover both minor and major defects of OT analyses that could all too easily remain unspotted otherwise. The formal specification of GEN and CON itself, a necessary first step before using OT SIMPLE to run analyses on inputs, promises additional return value in terms of enhanced clarity and precision in OT analyses.

7 Implementation

The following sections discuss some of the technical issues that were important in implementing OT SIMPLE and seem particularly worth noting. Together with the full source code listing in the appendix, these remarks should help the knowledgeable reader to modify and extend OT SIMPLE to suit his or her purposes. They may be skipped by a reader who is only interested in the business of formalizing and testing OT analyses on a computer.

7.1 Major ideas for implementing GEN in Prolog

This section presupposes some basic knowledge in logic programming, in particular Prolog.

GEN has been realized in a freely available variant of Prolog called BinProlog (Tarau 1996). As a platform for active research in logic programming, BinProlog has nevertheless stabilized over the years, evolving into a very useful programming language. There are four properties that made it especially suited for GEN implementation, as compared to other Prolog implementations:

BinProlog

- has a particularly efficient implementation of Definite Clause Grammars (DCGs)
- allows for multiple DCG input streams

- contains linear logic constructs, especially linear assumption
- provides for easy runtime system generation and C-ification

We will see the significance of each of these advantages later on.

The implementation of GEN divides into two tasks. One is the compilation of the external, human-readable notation for GEN grammars into an internally usable format. The other consists of the generation process itself, which is given an input and delivers the set of output candidates for that input on the basis of a previously compiled GEN grammar. Let us first describe the important aspects of the compilation process in what follows.

Iterating over the context-free rules in the GEN grammar, which is consulted as an ordinary Prolog file, a corresponding Prolog clause is asserted into the Prolog database for each rule. However, rules fall into two classes depending on their left-hand side (LHS). If a rule is labelled with an input marker `Marker # mother ---> daughters`, one must somehow ensure that during the generation process the rule will be used only once for every occurrence of `Marker` in the triggering input. This is markedly different from the desired behaviour for rules that have an ordinary nonterminal as their LHS symbol, since these should in principle be indefinitely reusable during a derivation. Therefore, although both types of rules are converted into clausal form, the first type is embedded under `#/2` clauses with markers retained, while the second type gives rise to predicate definitions where the LHS symbol directly functions as the head functor. This means that unlabelled rules-as-clauses are directly usable in a consecutive generation process, while labelled clauses must be activated depending on the input. The process of activation will be explained below.

A derivation starts from the distinguished startsymbol (if a declaration to that effect was present) or from the default startsymbol `word` otherwise. Therefore the `generate(Tree)` definition that is compiled takes into account which of the two cases applies. The main result of a derivation is its derivation tree (also known as a syntax or parse tree), built on the fly as a side effect of a successful Prolog deduction starting top-down from the startsymbol goal. Therefore a distinguished argument of the clause head corresponding to each rule is used to construct that tree in Prolog term format, taking the LHS category as functor while equating the term arity with the number of daughters on the right-hand side of the rule (see Pereira & Shieber 1987:74).

The generation process caters for automatic underparsing and bounded epenthesis. It must also make sure that inputs are consumed only once during a derivation and that linear precedence (LP) relations implicit in the ordered input are maintained. Finally, all possible derivations consistent with the current GEN grammar must be output for a given input, each derivation tree corresponding to a candidate of the rich GEN candidate set.

One-time input consumption in this implementation corresponds to clauses that are marked as being usable only once in a Prolog deduction, vanishing upon backtracking. This is a nonstandard requirement that many current Prolog versions cannot express directly. However, BinProlog provides a predicate `assumel/1`, for linear assumption, which has exactly the desired effect. Using this predicate, one copy of the clausal form of a labelled rule is linearly assumed for each corresponding input marker, before actual generation starts. To facilitate automatic underparsing, disjunctively a second copy is assumed that differs only in its employment of a `{}` wrapper term. Ordering this disjunct second in the relevant predicate `assume_terminals_from_input` means that due to Prolog's SLD proof strategy, candidates with more underparsing always appear later than those with less underparsing. This is a desired result in the face of typically limited amount of underparsing in actual winners – candidates with minimal underparsing should therefore be found near the beginning of the candidate stream in order to ease human inspection.

An important second requirement was to preserve the transitive LP relations implicit in the input. Since GEN input is converted to linearly assumed one-time clauses, thus existing on the level of grammar rules during actual generation, no *technical* input has been necessary sofar. Therefore, we are still free to use the DCG input stream for our own purposes. The key idea is to reflect the LP relations[18] by pairing GEN input positions with successive natural numbers, and setting the DCG input stream to the list of natural numbers thus obtained. Extending our description of the compilation of linearly assumed clauses corresponding to inputs, each such clause body is additionally specified to consume exactly one position of the DCG input stream, which is required to unify with the positional index that gave rise to it. E.g., in our `[h,'O',n,d]` example, the rule corresponding to `n` can only be used in a derivation if the next element that is not yet consumed is 3. Hence, the top-down generation process is simultaneously one of parsing, consuming the LP-encoding list. It is one of the virtues of declarative programming languages like Prolog that such simultaneity of top-down and bottom-up processing regimes requires no special programming effort.

Given this much insight into the inner workings of GEN, it should be quite

[18]Taking our running example for illustration, in every candidate for `[h,'O',n,d]`, `h` must be ordered left of each of `'O',n,d`, `'O'` must precede `n,d` in the tree yield and so on.

easy to see now what bounded epenthesis corresponds to. We simply treat epenthetic elements as another, but formally related, type of input. This first of all means that we must linearly assume N clauses with head `empty([])` to model a case when exactly N epenthetic elements are to be integrated into a tree derivation. Perhaps more surprisingly, indexing epenthetic elements with natural numbers exactly as in the previous case also makes sense. The reason is that when repeatedly backtracking over a set of identical assumed clauses Prolog would eventually try each possible matching order between rule goals (in this case `empty/1`) and stored clauses, leading to uninformative spurious ambiguity. Imposing a total order on the epenthetic pseudo-input to be respected by derivations effectively removes such unwanted ambiguity. Put another way, positional indexing of both the GEN input proper and the epenthetic elements helps keep the GEN output a true set, with multiple copies of the same element being disallowed. The only difference of `empty` clauses comes when consuming epenthetic pseudo-input: we need to switch from the default DCG input stream to a second DCG stream for epenthetic positions, consume one element that must unify with the stored index position, then switch back to the default stream. This ability to switch back and forth between multiple DCG inputs is a distinct advantage of BinProlog's nonstandard implementation of Definite Clause Grammars. We will see another potential application of input stream switching in section 8.2.

Putting the pieces together is now really simple. A distinguished predicate `gen_workhorse` fills both DCG input streams with their respective index lists, as derived from GEN input and the user-specified number of epenthetic elements. Then it tries to prove the goal `generate(Tree)` whose body contains the start symbol of the GEN grammar, using the standard depth-first left-to-right proof strategy of Prolog. The proof is deemed successful if both input streams have been fully consumed, instantiating `Tree` as a side-effect, which can then be output. In a failure-driven loop, all different ways of proving a derivation from the start symbol are found, with concomitant candidate output contributing to the richness of GEN. Another iteration on top of this workhorse predicate enumerates the epenthetic possibilities, starting from no epenthesis to the maximal number of epenthetic elements that was specified by the user.

An additional technical quirk is due to special BinProlog behaviour in connection with assumed clauses. Since assumed clauses override all compiled and asserted clauses with the same head, an unlabelled rule with the same LHS as a labelled one would under normal assertion into the Prolog database not be visible if a corresponding marker label appeared in the GEN input. Therefore we need to lift these unlabelled rules to the same level as labelled ones to prevent invisibility due to overriding. Fortunately, a twin predicate of linear assumption does exists in BinProlog, `assumei/1` for intuitionistic assumption, which in contrast to the linear logic construct can be used an indefinite number of times in proofs, but also vanishes on backtracking. We therefore modify the compilation of these unlabelled rules accordingly by deferring actual clause assertion in favour of recording a 'promise' to activate clauses. Activation then simply amounts to using the 'promise' facts at actual generation time to intuitionistically assume each of the clauses so promised, with the effect that same-LHS labelled and unlabelled rules can coexist as desired.

Finally, BinProlog provides a variety of ways to turn Prolog programs into standalone applications, in particular by C-ification of both the program and the necessary parts of BinProlog. This means that we can turn the GEN implementation into a directly executable piece of software which, when constructed carefully, can run on systems that do not have BinProlog installed. See the BinProlog manual (Tarau 1996) for details.

7.2 Issues in implementing constraint action

The basic idea of implementing CON was very simple, using 'sed' scripts to specify finite-state-transducers that map selected portions of candidate trees to violation marks. A substantial point not discussed so far is the severity of the limitation imposed by the regularity assumption for constraints, a limitation that is shared by all current work that is explicit about formal constraint specification.

Ellison (1995) has shown that the widely used family of Generalized Alignment constraints (GA, McCarthy and Prince 1994a) cannot be described with regular language expressions, in contrast to the constraints we have seen so far. While such qualitative difference in formal language class in an innocuously-looking constraint family such as GA is certainly surprising from the viewpoint of informal OT, the result obviously needs further investigation in the present context. In fact, there is some hope that GA constraints can be modelled using 'sed', because some of its operations that were hitherto unused in the main part of constraints go beyond regular power (a case to remember is the *copying* of a previously stored candidate of a priori unknown length, to be later inserted before the violation vector in the constraint epilogue).

Also it is natural to ask whether the notion of *correspondence* and its associated constraint families (McCarthy and Prince 1994b et alia) can be incorporated into OT SIMPLE. While this interesting problem must be left for further research, a general idea that suggests itself is to compactify correspondence pairs (or even N-tuples of correspondents) via some sort of difference structures, in order to retain a sensible definition of locality of corresponding elements for the constraints.

7.3 Issues in the implementation of EVAL

We have seen that simple sorting suffices to model EVAL, here narrowly understood as denoting the harmony maximization part proper. However, there is room for improvement, since we did not take any actions to *prune* the set of candidates after each evaluation of a constraint, corresponding to the '!' graphical device used in OT tableaux to indicate fatal violation. Recall that pruning exploits the familiar characteristic of EVAL that, due to OT's strict domination regime, at any point in the constraint hierarchy only those output candidates need to be retained that still tie for optimality.

We have in fact experimented with a shell script implementation of such a PRUNE operator, constructed using only standard UNIX tools. The idea was to sort the incoming candidate set on the basis of the partial violation vector constructed so far, then examine the first line of the sorted candidate stream to extract the currently optimal violation vector. After converting the vector into regular expression format, we could then filter the candidate stream with the UNIX tool 'egrep', using the regular expression just constructed, thereby literally deleting non-optimal candidate lines. Due to the overhead incurred from shell script interpretation and the usage of generic tools, however, the use of PRUNE after each constraint evaluation turned out to be actually slower, at least for small-scale examples. In order to be able to process huge candidate sets, in the long run a more efficient implementation of PRUNE is desirable.

Finally, there are cases when the constraint hierarchy is not a total ordering relation over CON. Since we can compose any partial order from the union of suitable total ordering relations, it currently seems best to manually form the set union of the winners corresponding to each total order, as computed by OT SIMPLE. Of course, this step would be easy to automatize if desired.

8 Extensions

For the immediate future we foresee two specific extensions that are already known to be relatively easy to implement. We motivate both of them in the following and sketch their implementation.

8.1 Prespecification of structure

Prespecification[19] of structure that would be assigned anyway in some candidates by GEN is an effective means to limit the size of the GEN set over which CON and EVAL must operate, with obvious practical advantages for analysis construction and debugging. It can also be seen as a facility for implementing the *results* of Lexicon Optimization – a procedure to infer optimal inputs from surface forms (Prince and Smolensky 1993, ch.9) –, since Inkelas (1994) has pointed out an important connection between Lexicon Optimization and the possibility of prespecifying predictable non-alternating structure underlyingly.

The implementation of prespecification capitalizes on the possibility of specifying partial trees as partially instantiated Prolog terms. Since `generate(Tree)` returns a fully instantiated tree after derivation, unifying the `Tree` with the prespecified partial tree before generation should be an effective forward-checking way of enforcing the restrictions imposed by prespecification. The question that remains then is what a suitable formal language should look like that enables users to describe such incomplete trees in an intuitive fashion. One good candidate would be a kind of modal language, using prefix operators `up,down,left,right` to wander around the tree from some designated starting node, while mentioning restrictions on the identity of the category nodes that are visited. A hypothetical example expression in such a language might be `right syl up ft left ft up up phrase` ('to my right, I see a syllable that is dominated by a foot whose left-hand sister is another foot that itself is dominated by a phrase located two nodes above').

8.2 Multiple input streams

We have already seen that internally the GENeration mechanism makes use of two distinct DGC input streams that correspond to real GEN input (or,

[19] Thanks to Chris Golston for suggesting this extension, prompted by a demonstration where hundreds of output candidates flooded the computer screen.

more precisely, the list of input positions) and epenthetic pseudo-input. This was possible because of the general provision of up to 255 distinct input streams in BinProlog, between which one can switch back and forth at will in a DCG application.

Now, for cases like the celebrated Tagalog *um* infixation analysis of Prince and Smolensky (1993, ch.4) and similar instances of mobile or floating morphemes that can be analyzed as underspecified w.r.t. linear precedence, this BinProlog feature again seems entirely appropriate. Each such floating element would be assigned its own ordered input stream, and the GEN mechanism would pick nondeterministically from the totality of input streams arising from the current GEN input, just as it nondeterministically selected among parsed and underparsed variants of input items. While thereby all possible intercalations of input streams would be output, the order of each individual input stream could still be preserved by positional indexing, as detailed above. With more articulate categorial information in both the appropriate input and GEN grammar specification – at least including morphological tags to distinguish e.g. stems from affixes – constraints could then be straightforwardly implemented to handle Tagalog *um* and similar analyses.

9 Conclusion

We have described a particularly simple approach to the computer implementation of classical OT. It is the first we know of that is publicly available, yet offers generic mechanisms to specify constraints and GEN structural grammars while simultaneously being geared towards practical usage. Simplicity in implementation in particular stems from reusing standard system software for CON and EVAL as well as from choosing BinProlog as a suitable programming platform for GEN. Due to the level of formal detail involved, working with OT SIMPLE may present initial difficulties to some, specifically when it comes to the task of formalizing constraints. Still, the overall behaviour and look-and-feel of this software tool should be close enough to the original presentation of OT to make OT SIMPLE fairly intuitive to use. It is therefore hoped that OT enthusiasts will indeed employ it to develop and test implemented and formally sound OT analyses, both for their own merit and possibly also in the classroom, invent new constraint coding techniques beyond those described and suggest further improvements and extensions.

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A Appendix

This section contains first of all the source code for GEN, written in BinProlog and contained in the current OT SIMPLE distribution as file `gen.pl`. The following three shell scripts encapsulate technical details of the actual GEN, CON and EVAL invocations, which provide the user interface to OT SIMPLE that was described earlier.

gen.pl

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%                                                              %%%
%%%         File: gen.pl                                         %%%
%%%       Author: Markus Walther                                 %%%
%%%      Purpose: Model GEN component of OT in BinProlog         %%%
%%%    Copyright: Seminar fuer Allgemeine Sprachwissenschaft     %%%
%%%               Universitaet Duesseldorf, 1996                 %%%
%%%                                                              %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% LOAD: $ bp -q 6
%%%       ?- compile(gen).


%%% KNOWN DEFICIENCIES
/*
        - empty positions can not be underparsed.
        - no explicit sharing
        - Multiple identical labels don't work: textually later rules
        are not catered for during input processing; e.g. in

        l # ons ---> "l".
        l # coda ---> "l".

        the second marked rule is never used.

*/

%%% OPERATORS

:- op(1200,xfy,('#')).
:- op(1150,xfx,('--->')).
:- op(900,fy,(gen)).
:- op(900,fy, (genload)).
:- op(900,fy, (startsymbol)).
```

```
%%%
% A SIMPLE REALIZATION OF OT'S GEN
%%%

% --- interactive GEN

gen(Input) :-
  write('Enter max. number of epenthetic positions, followed by period: '),
  read(NumberOfEpenthetic),
  gen(Input, NumberOfEpenthetic).

% --- non-interactive GEN
% --- enumerates candidates with increasing number of epenthetic elements

gen(Input, MaxNumberOfEpentheticPositions) :-
        MaxNumberOfEpentheticPositions >= 0,
        nl,
        for(CurrentNumberOfEmptyElements, 0, MaxNumberOfEpentheticPositions),
        gen_with_empty_structure(CurrentNumberOfEmptyElements, Input),
        fail.
gen(_,_) :- nl.

% --- GEN with structural grammar preload

gen(GrammarFile, Input, MaxNumberOfEpentheticPositions) :-
        genload(GrammarFile),
        gen(Input, MaxNumberOfEpentheticPositions).

gen_with_empty_structure(Exactly_N_Empties, Input) :-
        assume_n_empties(Exactly_N_Empties, Exactly_N_EmptyPosList),
        assume_terminals_from_input(Input, PosList, 1),
        assume_static_terminals_from_grammar,
        gen_workhorse(PosList, Exactly_N_EmptyPosList).

assume_static_terminals_from_grammar :-
        retract(to_be_assumed(Clause)),        % fetch Clause from database
        assumei(Clause),                       % intuitionistic assume
        assume_static_terminals_from_grammar,  % recurse
        assertz(to_be_assumed(Clause)),        % re-store Clause in database
        !.
assume_static_terminals_from_grammar.

assume_terminals_from_input([],[], _) :- !.
assume_terminals_from_input([Marker|Markers], [I|PosList], I) :-
        ( ( Marker # (LHS :- RHS) ) -> true
        ; write('%%% ERROR: Input element '), write(Marker),
          writeln(' triggers (#) no rule in the grammar!'),
          abort
        ),
```

```
        ( assumel((LHS :- RHS, dcg_connect(I)))
        ; functor(LHS, F, 1), functor(UnderparsedLHS, F, 1),
          arg(1, LHS, LHSArg), arg(1, UnderparsedLHS, {LHSArg}),
          assumel((UnderparsedLHS :- RHS, dcg_connect(I))) %%% UNDERPARSING
        ),
        J is I + 1,
        assume_terminals_from_input(Markers, PosList, J).

assume_n_empties(0,[]) :- !, assumel((empty(_) :- fail)). %% suppress
                                                           %% undefined empty/1
                                                           %% warnings
assume_n_empties(N,[N|More]) :-
        M is N-1,
        assumel((empty([]) :- dcg_tell(2), % switch to epenth. elem. stream
                              dcg_connect(N), % consume one elem.
                              dcg_tell(1))), % switch back to input stream
        assume_n_empties(M,More).

gen_workhorse(PosList, EmptyPosList) :-
        dcg_tell(2),                  % switch to epenth. elem. stream
        dcg_def(EmptyPosList),        % define list of numbered epenth.elems
        dcg_tell(1),                  % switch to real input stream
        dcg_def(PosList),             % define input positions to be parsed
        generate(Tree),               % run DCG, thereby instantiating Tree
        dcg_tell(1),                  % check that input
        dcg_val([]),                  % has been consumed, i.e. parse success
        dcg_tell(2),                  % check that all epenthetic elems
        dcg_val([]),                  % have been parsed/integrated as well
        gen_output(Tree),             % output Tree
        fail.                         % backtrack

gen_output(Tree) :-
        write(Tree),                  % tree in Prolog term repres,
        put(46),                      % followed by single dot;
        nl.                           % each tree on separate line

initialize :-
        abolish_dynamic_predicates.

abolish_dynamic_predicates :-
        current_predicate(Pred,PredTerm),
        predicate_property(PredTerm, (dynamic)),
        functor(PredTerm, _Functor, Arity),
        abolish(Pred, Arity),
        fail.
abolish_dynamic_predicates.

%%
% PREDICATES BELONGING TO GEN GRAMMAR FILE COMPILATION
```

```
% A Gen grammar is compiled into a DCG in efficient hidden accumulator format
% provided by BinProlog. The DCG constructs a syntax tree as a side effect
% while parsing input. This syntax tree is the main result for
% purposes of constraint evaluation, which itself is done outside of Prolog.
%%

% --- expand surface notation to internal

term_expansion( (Head0 ---> Body0), (Head :- Body)) :-
        !,
        compute_rhs(Body0, Body, BodyVars, BodyLength),
        functor(Head1, Head0, BodyLength),
        compute_lhs(BodyVars, Head1, 1),
        functor(Head, Head0, 1),
        arg(1, Head, Head1),
        !.

% --- compute right hand side (rhs) of rule

compute_rhs((First0,Rest0), (First,Rest), [FirstArg|RestArgs], Len) :-
        !,
        process_term(First0, First, FirstArg),
        compute_rhs(Rest0, Rest, RestArgs, RestLen),
        Len is RestLen + 1.

compute_rhs(Single0, Single, [SingleArg], 1) :-
        process_term(Single0, Single, SingleArg).

% --- process individual item in rhs of a rule

process_term(Single0, Single, SingleArg) :-
        ( atomic(Single0) ->
                functor(Single, Single0, 1),
                arg(1, Single, SingleArg)
        ; name(SingleArg, Single0), Single = true
        ; writeln('%%% ERROR: right hand side categories in rule can only be'),
          writeln('%%% atoms, numbers or strings! Found "'),
          write(Single0), write('" instead.'),
          Single = grammar_error(SingleArg),
          SingleArg=here
        ).

% --- compute left hand side (lhs) of rule

compute_lhs([], _, _) :- !.
compute_lhs([FirstVar|RestVars], Head, I) :-
        arg(I, Head, FirstVar),
        J is I+1,
        compute_lhs(RestVars, Head, J).
```

```
translate_gen_grammar :-
        ( (H ---> B), NonVarMarker=true % unmarked rule
        ; '#'(Marker, (H ---> B)),      % rule labelled with Marker
          ( nonvar(Marker) -> NonVarMarker=true
          ; NonVarMarker=false
          )
        ),
        ( ( call(NonVarMarker),                  % Marker was wellformed
            term_expansion(( H ---> B ), Clause) % translate rule to internal
          )  ->
              put(46)                            % progress report
        ; writeln('%%% WARNING: The following rule could not be translated '),
          writeln('%%% '), write((H ---> B)),
          Clause = '$no_legal_rule'
        ),
        ( atomic(Marker) ->             % a marked rule
              assertz((Marker # (Clause))) % assert marker+rule translation
        ; '#'(_Marker, (H ---> _)) ->   % an unmarked rule for which a marked
                                        % one with same lhs exists
              assertz(to_be_assumed(Clause)) % mark rule translation as
                                           % special since assumed preds
                                           % override dynamic ones
        ; assertz((Clause))             % default: unmarked rule, enter transl.
        ),
        fail.                           % backtrack

translate_gen_grammar :-
        ( startsymbol(Start) ->         % explicit startsymbol decl. exist
              functor(Startsymbol, Start, 1),        % construct start
              arg(1, Startsymbol, Tree),             % category;
              assert((generate(Tree) :- Startsymbol)) % enter start pred.

        ; assert((generate(Tree) :- word(Tree))),      % enter default start
          writeln('%%% WARNING: No explicit startsymbol declaration found.'),
          writeln('%%%          Assuming "startsymbol word." as default.')
        ).

genload(GenGrammarfile) :-
  initialize,
  (            % construct full file name  from abbreviated GenGrammarfile
    name(GenGrammarfile, FileString0),
               %           .  g   e    n   filename extension
    det_append(FileString0, [46,103,101,110], FileString),
    name(File, FileString),
    consult(File) ->
                        write('%%% Translating Gen grammar file '),
                        ( translate_gen_grammar ->
                                nl, writeln('%%% Gen translated.')
```

```
                        ; nl, writeln('%%% Translation error.')
                        )
  ; writeln('%%% Gen grammar file name (*.gen) incorrect or file not found')
  ),
  nl.

help :-

writeln('%%%                   OT SIMPLE / GEN version 1.0'),
writeln('%%%                   ---------------------------'),
writeln('%%% (c) 1996 Markus Walther (walther@ling.uni-duesseldorf.de)'),
writeln('%%%'),
writeln('%%% LOAD   GEN   GRAMMAR   WITH E.G. ?- genload hessian. <Return>'),
writeln('%%% GENERATE   FROM  INPUT WITH E.G. ?- gen [h,''O'',n,d]. <Return>'),
writeln('%%% EXIT OT SIMPLE / GEN   WITH      ?- halt. <Return>'),
writeln('%%% THIS    HELP  MESSAGE  WITH      ?- help. <Return>'),
writeln('').


% --- support predicates

writeln(Term) :- nl, write(Term).

:- help.
```

GEN

```
#!/bin/sh
# GEN Generate candidates from grammar, input and epenthesis count
# ===
# Usage: GEN "grammarfile, InputAsPrologList, MaxEpenthetics"
#
# First, issue compile statement for gen.pl, then compose three-parameter
# gen/3 goal (e.g. "hessian, [h,'O',n,d], 1" as instantiation for $1);
# send these directives to BinProlog (bp) with high quietness level (-q 6);
# remove superfluous Prolog prompt (?- ) and response (yes) as well as
# Prolog comment-initial (%%%) and stray empty lines (^$) with 'sed' afterwards

echo "compile(gen). gen($1)." | \
bp -q 6 | \
sed -e 's/?- //g;s/^yes//g;s/^%%%.*$//;/^$/d'
```

CON

```
#!/bin/sh
# CON   implement constraint action
# ===
```

```
# Usage: CON Con1 Con2 ... ConN
# Con i denotes the name of a constraint script;
# We want to connect all of these ($*) as arguments to a single
# 'sed' invocation; since the syntax is
# sed -f scriptfile1 -f scriptfile2 ... -f scriptfileN,
# we use *another* invocation (`echo ... | sed ...`) of sed to
# intersperse these  -f strings via substitution of the blanks
# argument separators;
# With the argument specification thus refined we can finally
# invoke 'sed' (the first one in the line) to act on the
# constraint scripts

sed `echo " $*" | sed -e 's/ / -f /g'`
```

EVAL

```
#!/bin/sh
# EVAL  evaluate CON-annotated output candidates
# ====
# Usage: stream_of_candidates | EVAL
# violation vector column is identifiable through field separator character '.'
# The column to sort on is the second column (first is the candidate itself)

sort -t. +1 -2
```