Robust Stochastic Parsing Using the Inside-Outside Algorithm

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1 Introduction

Development of a robust syntactic parser capable of returning the unique, correct and syntactically determinate analysis for arbitrary naturally-occurring input will require solutions to two critical problems with most, if not all, current wide-coverage parsing systems; namely, resolution of structural ambiguity and undergeneration. Typically, resolution of syntactic ambiguity has been conceived as the problem of representing and deploying non-syntactic (semantic, pragmatic, phonological) knowledge. However, this approach has not proved fruitful so far except for small and simple domains and even in these cases remains labour intensive. In addition, some naturally-occurring sentences will not be correctly analysed (or analysed at all) by a parser deploying a generative grammar based on the assumption that the grammatical sentences of a natural language constitute a well-formed set (e.g. Sampson, 1987a,b; Taylor et al., 1989). Little attention has been devoted to this latter problem; however, the increasing quantities of machine-readable text requiring linguistic classification both for purposes of research and information retrieval, make it increasingly topical. In this paper, we discuss the application of the Viterbi algorithm and the Baum-Welch algorithm (in wide use for speech recognition) to the parsing problem and describe a recent experiment designed to produce a simple, robust, stochastic parser which selects an appropriate analysis frequently enough to be useful and deals effectively with the problem of undergeneration. We focus on the application of these stochastic algorithms here because, although other statistically based approaches have been proposed (e.g. Sampson et al., 1989; Garside & Leech, 1985; Magerman & Marcus, 1991a,b), these appear most promising as they are computationally-tractable (in principle) and well-integrated with formal language / automata theory.

The Viterbi algorithm and Baum-Welch algorithm are optimised algorithms (with polynomial computational complexity) which can be used in conjunction with stochastic regular grammars (finite-state automata, i.e. (hidden) markov models, Baum, 1972) and with stochastic context-free grammars (Baker, 1982; Fujisaki et al., 1989) to select the most probable analysis of a sentence and to (re-)estimate the probabilities of the rules (non-zero parameters) defined by the grammar (respectively). The Viterbi algorithm computes the maximally probable derivation with polynomial resources despite the exponential space of possible derivations (e.g. Church & Patil, 1983) by exploiting the stochastic assumption and pruning all non-maximal paths leading to the set of states / non-terminals compatible with the input at each step in the parsing process. The Baum-Welch algorithm (which is often called the forward-backward algorithm when applied to regular grammars and the inside-outside algorithm with context-free grammars) computes the probability of each possible derivation with polynomial resources also by factoring the computation across each state / non-terminal involved in any derivation. A detailed and clear description of these algorithms is provided by de Rose (1988), Holmes (1988) and Lari & Young (1990), amongst others. These algorithms will converge towards a local optimum when used to iteratively re-estimate probabilities on a training corpus in a manner which maximises the likelihood of the training corpus given the grammar.

It is possible to imagine exploiting these algorithms in a number of ways in text processing and parsing and, so far, relatively few of the possible options have been explored. To date the primary application of stochastic techniques in text rather than speech processing has been the use of the Viterbi algorithm in the lexical tagging of corpora with part-of-speech categories, training on an unambiguous corpus (e.g. de Rose, 1988). Typically a tagged training corpus is used to train a bigram (first-order) ergodic automaton (i.e. no parameters are set to zero, which is equivalent to assuming that no grammatical constraints are assumed other than those imposed by the choice of tagset). This represents one of the simplest applications of such stochastic techniques, because the unambiguous training data ensures that the model will converge to the true optimum and the ergodic assumption ensures that all possible derivations will involve the same number of states for any given length of input. Recently, Cutting et al. (1992) have developed a tagging system based on the Baum-Welch algorithm trained on untagged data which performs as well as these Viterbi based systems. In what follows we will only consider the application of these algorithms to stochastic context-free grammars (SCFGs) and extensions of such models, since we are addressing problems of parsing rather than tagging.

2 Choosing Between Analyses

Fujisaki et al. (1989) describe a corpus parsing experiment using a SCFG containing 2118 rules which was first converted into Chomsky Normal Form (CNF) (creating 7550 productions) and then trained on an ambiguous corpus of 4206 sentences using a variant of the Baum-Welch re-estimation procedure. In this case the model was constrained in the sense that many of the possible parameters (rules) defined over the category set were set to zero before training began. Thus training was used only to estimate new probabilities for a set of predefined rules. The utility of the resulting probabilities was evaluated by testing the trained grammar on sentences randomly selected from the training corpus, using the Viterbi algorithm to select the most probable analysis. In 72 out of 84 sentences examined, the most probable analysis was also the correct analysis. 6 of the remainder were false positives and did not receive a correct parse, whilst the other 6 did but it was not the most probable. A success rate (per sentence) of 85% is apparently impressive, but it is difficult to evaluate properly in the absence of further details concerning the nature of the corpus. For example, if the corpus contains many simple and similar constructions, training on ambiguous data is more likely to converge quickly on a useful set of probabilities. (Fujisaki et al. report that the majority of their corpus had an average sentence length of 10.85 words.)

Sharman et al. (1990) conducted a similar experiment with a grammar in ID/LP format. ID/LP grammars separate the two types of information encoded in CF rules — immediate dominance and immediate precedence — into two rule types which together define (a subset of) the CFLs. This allows probabilities concerning dominance, associated with ID rules, to be factored out from those concerning precedence, associated with LP rules. In this experiment, an unambiguous training corpus of sentences paired with a semantically appropriate syntactic analysis was employed consisting of about 1 million words of text. A grammar containing 100 terminals and 16 non-terminals and initial probabilities based on the frequency of ID and LP relations was extracted from the training corpus. The resulting probabilistic ID/LP grammar was used to parse 42 sentences of 30 words or less drawn from the same corpus. In addition, lexical tag probabilities were integrated with the probability of the ID/LP relations to rank parses. 18 of the most probable parses (derived using a variant of the Viterbi algorithm) were identical to the original manual analyses, whilst a further 19 were 'similar', yielding a success rate of 88%. What is noticeable about this experiment is that the results are not significantly better than Fujisaki et al.'s experiment with ambiguous training data discussed above, despite the use of more unambiguous training data, a more sophisticated language model and a grammar derived directly from the corpus (thus ruling out undergeneration). It seems likely that these differences derive from the differential complexity of the corpus material used for training and testing, properties of the grammars employed, and so forth. However, these two results underline the need for the use of shared corpora in training and testing, or model / grammar independent measures of complexity, such as estimation of the actual entropy / perplexity of a language (Sharman, 1990; Wright, 1990).

Briscoe & Carroll (1991, 1992) extend the probabilistic approach to stochastic generalised LALR(1) parsers. The motivation for this move is that LR parse tables (which are non-deterministic finite-state automata in the generalised case) provide a more fine-grained stochastic model than SCFGs and can distinguish probabilistically derivations involving (re)application of identical grammatical rules (such as in typical analyses of noun-noun compounding or PP attachment) in different orders. Thus they offer a better approximation to natural language without abandoning the stochastic assumption and consequent computational advantages. They construct a LALR(1) parse table from the CF backbone of the Alvey Natural Language Tools (ANLT) grammar, a wide-coverage unification-based grammar (e.g. Briscoe et al., 1987) and derive a probabilistic version of the table by interactively guiding the LR parser to the semantically appropriate analysis of the training data (i.e. an unambiguous training corpus is semi-automatically created using the parser / grammar to be trained). The resulting LR parse histories are used to associate probabilities with the table directly (in contrast to Wright (1990) and others, who have proposed to 'compile' the probabilities associated with a SCFG into the LR table). In principle, the Viterbi algorithm could be used to find the most probable analysis assigned by the CF backbone, however, in practice during both the training and testing phase, features associated with the CF backbone rules are unified, and unification failure results in the associated derivation being assigned a probability of zero. Consequently, a packed parse forest representation is constructed with probabilities associated with (sub)analyses in the forest and the parse forest is probabilistically unpacked to recover the the n-best parses (Wright et al., 1991; Briscoe & Carroll, 1992). This approach was tested on a corpus of noun definitions taken from the *Longman Dictionary of Contemporary English* (LDOCE) training on 151 definitions and testing on 63 definitions from the training data and a further 54 unseen definitions. The definitions vary in length from 2 to 31 words and in global ambiguity from unambiguous to over 2500 distinct analyses. On the seen test data the most probable parse was correct in 85.9% of the cases and for the unseen ones in 63.8% of cases. In the case of the unseen data most of the failures are false positives in which no correct analysis is found and in the remaining cases the correct analysis is most frequently one of the three most probable analyses. In the case of the false positives the most frequent cause of failure was the lack of a subcategorisation frame in the set of lexical entries associated with a word.

Each of these (very preliminary) experiments suggests that stochastic approximation may be useful in selecting an appropriate parse from the set licensed by a generative grammar. However, none achieve results reliable enough to be of practical utility and none address the problem of undergeneration or grammar induction via stochastic techniques in a manner analogous to work in speech recognition or lexical tagging. Nevertheless, the experiment reported in Briscoe & Carroll highlights the need to resolve this problem before parsers can genuinely be robust.

3 Dealing with Undergeneration

The stochastic techniques presented above whilst being useful the disambiguation of analyses, are as 'brittle' as non-stochastic approaches when presented with new examples, for which the correct analysis cannot be assigned, or in the limit, for which no analysis is possible. These situations may arise, through a deficiency in the syntactic rules or lexicon, or simply where the input is ill-formed or extragrammatical. One approach to this problem, is to iteratively develop the grammar, adding suplementary rules, and re-analysing the failed examples (e.g. Black et al. 1992). The aim here is to ensure broad coverage by the labour intensive analysis of as large a subset as possible of the target language. In more lexically-orientated approaches to grammar, it might be argued that the principle cause of undergeneration is the incompleteness of lexical entries (Briscoe & Carroll, 1991). However, manual correction or development of a realistic lexicons does not appear feasible, given the vast amount of coding required (Boguraev & Briscoe 1989), and there are good reasons to believe that the goal of developing an entirely watertight generative grammar is unattainable (Sampson, 1987a; Taylor et al., 1989).

Methods for dealing with ill-formedness have been presented for formal languages (Tanaka & Fu, 1978), stochastic pattern recognition (Fu, 1982), and in natural language processing (Mellish, 1989). Most of these address the problem through the inclusion of simple rules, which support deletion, insertion or substitution of terminals, combined with penalty scores for their use. Where the ill-formedness is of a more complex nature, however, the use of thsee techniques will lead to combinatorial explosion (where multiple deletions or insertions are hypothesised for instance).

Another potential solution to the problem of undergeneration using the inside-outside algorithm is suggested by the work of Lari & Young (1990). They utilise a tabular parsing algorithm (e.g. CYK) coupled with a SCFG in CNF. Initially, they assume that all possible CNF rules which can be formed from a prespecified terminal and non-terminal category set are possible; that is, are associated with non-zero probabilities. The inside-outside algorithm is used to re-estimate the probabilities of these rules by repeated iteration over a corpus until they stabilise within some prespecified threshold. In this way a (locally) optimal set of rules and probabilities is induced which maximise the probability of the language defined by the corpus. Thus they propose an approach which is the CF counterpart of making the ergodic assumption in (hidden) markov modelling.

One problem with this technique is that the search space of possible parses even for small category sets is very large; although the algorithm has $O(n^3)$ complexity in the length of the input and number of non-terminals, the search space of possible analyses is defined by the the number of binary branching trees over a sentence of length n (the Catalan series, Church & Patil, 1983) multiplied by the number of possible labellings of the nodes in that tree (the number of non-terminals to the power of n-1). For this reason the algorithm is only practical for small (non-terminal) category sets. Lari & Young generated a corpus of 200 random palindromes from a grammar containing 5 non-terminals, two terminals and 8 rules (non-zero parameters) for the simple palindrome language $\{xy|x \text{ is a mirror image of } y\}$. The same category set with all 135 possible rules (parameters) given initial non-zero probabilities was used to re-estimate the grammar. After approximately 70 iterations the system stabilised on a weakly-equivalent grammar for this language. Lari & Young (1990) demonstrate that this grammar is a better model of the observed language than that produced by a hidden markov model with the same number of parameters, in the sense that the predicted entropy of the language is lower. Unsurprisingly, the CFG is also better able to classify members of the palindrome language since this language cannot be generated using a regular grammar. It is fairly clear that scaling up Lari & Young's approach for a realistic grammar of natural language, such as the ANLT grammar, would be computationally intractable — the ANLT CF backbone contains 575 distinct categories (before conversion to CNF). It might be thought that switching to the Viterbi algorithm would allow a considerable saving in computation since the latter only requires computation of the average and maximum probabilities for each sentence of the corpus for re-estimation. However, in order to achieve convergence it would almost certainly be necessary to use much more training data in this case, because less information is being extracted from each example. It would probably be necessary to use a smoothing technique to avoid unseen events converging to the zero threshold too rapidly. And, it is impossible to combine filtering of CF backbone parses by unifying the remaining features with the Viterbi algorithm, since this can mean that the most probable CF backbone analysis is invalid, necessitating backtracking through sub-optimal analysis paths.

One simplification would be to use lexical tagging of corpora to reduce the size of the terminal vocabulary and to make it unambiguous. It might then be possible to develop a grammar of the order of complexity of that typical used in the manual parsing of tagged corpora, such as the Lancaster skeleton parsing scheme (Leech & Garside, 1991) or the Penn Treebank scheme (Santorini, 1990). These schemes typically assume of the order of 10 non-terminal symbols; however, even grammars of this simplicity result in startlingly large search spaces when no grammatical constraints (other than CNF) are assumed; for instance, for a 20 word sentence and 10 non-terminals over a determinate lexical input there are $1.76726319 \times 10^{28}$ possible analyses and for a 30 word sentence $1.00224221665137 \times 10^{44}$. Although it is possible to perform re-estimation in parallel quite straightforwardly by splitting the corpus, these figures suggest that this approach may be too computationally expensive to be practical.

Another problem with Lari & Young's approach from the perspective of parsing is that it is extremely un-

```
FEATURE V{+, -}
FEATURE BAR{0, 1, 2}

ALIAS V2 = [V +, N -, BAR 2].
ALIAS V1 = [V +, N -, BAR 1].

PSRULE S1 : V2 --> N1 V1.
PSRULE VP1 : V1 --> V0 N1.

WORD cat : N0.
WORD the : DT.
```

Figure 1: Simple X-bar Grammar Rules

likely that the re-estimation process will result in a grammar which imposes constituency of a linguistically conventional kind. In the context of language modelling for speech recognition this is unimportant, but it is a crucial consideration for parsing. Even in the case of the very simple palindrome language experiment, the re-estimated grammar is not strongly-equivalent to the original one. In general, in order to obtain useful analyses of a language it will be necessary to start from initial probabilities which bias the system towards a linguistically-motivated local optimum during re-estimation.

4 Imposing Grammatical Constraints

In the limit, imposing grammatical constraints on the initial model used for re-estimation would reintroduce the problem of undergeneration and make the Lari & Young technique into one for the acquisition of probabilities from an ambiguous corpus for a completely prespecified grammar (as with the experiments described in section 2). However, it is possible to envisage an intermediate position in which some broad grammatical constraints are imposed and some rules are explicitly specified with higher initial probabilities, whilst implicit rules compatible with these constraints are assigned a floor non-zero probability, and illegal rules incompatible with the constraints are given zero probabilities. In this way, the search space defined over the category set can be reduced and the size of the category set can be increased, whilst the initial bias of the system will be towards a linguistically motivated (local) optimum. In what follows, we suggest several constraints and propose a general feature-based approach to their specification. The idea is that many constraints will have the property of ruling out linguistically uninterpretable analyses without necessarily constraining weak generative capacity.

4.1 Headedness

The notion of headedness as expressed, for example, in X-bar Theory (e.g. Jackendoff, 1977), can be formalised in a feature-based unification grammar containing rules of the type illustrated in Figure 2, which is specified in the ANLT formalism (e.g. Briscoe et al., 1987).

If we think of the word declarations as a set of unary rules, rewriting preterminals as terminals, and the aliased categories as atomic category symbols, G1 specifies a CNF CFG with 11 non-terminal and 20 terminal categories (given in full in appendix 1). If we were to induce a SCFG using the inside-outside algorithm from G1, raising the floor of probabilities in the matrix representation of the space of possible rules would force the following (and many other) rules to be considered and thus incorporated into possible analyses assigned by the parser:

```
N2 --> V2 V2        N2 --> P0 V1
A1 --> V2 N1        A1 --> P0
V2 --> N2 P1        V2 --> A0 A1
```

Linguistically, these rules are unmotivated and implausible for the same reason: they violate the constraint that a phrase must have a head; for example, a noun phrase (N2) must contain a noun (N), a sentence (V2) must contain a verb (phrase) (V1), and so forth. Of course, there are many more possible combinations of the category set for G1 which also violate this constraint and taken together they can be used to define a very large number of possible analyses of input sentences. Furthermore, the interpretation of such rules within any extant linguistic framework is impossible, so it is unclear what we would 'learn' if the system converged on them. However, if we impose the following constraint on formation of further rules in G1, then all of the above rules will be blocked:

```
CONSTRAINT HEAD1 :
      [N, V, BAR(NOT 0)] --> [], [];
      N(0)=N(1), V(0)=V(1),
      BAR(0)=(BAR(1) | BAR(1) -- 1).
```

This constraint expressed in terms of feature values is to be interpreted as a restriction on immediate dominance relations in CF rules consisting of a rule schema specifying that all rules must contain a non-(pre)terminal mother category and two non-terminal daughters, that all mother categories must be specified for N, V and BAR, and that one daughter must share these values or have a BAR value of one less than the mother. Thus this constraint also blocks rules containing heads with BAR values higher than that of the mother category. The utility of such rules is also dubious since they express linguistically implausible claims, such as the head of a phrase is a clause, and so forth. The constraint licenses rules not in G1 such as:

```
a)                  b)
V2 --> N2 V2        V2 --> V1 V1
V2 --> A1 V2        V2 --> P0 A1
V1 --> V0 V1        V1 --> V1 V2
N1 --> N0 V2        N1 --> N0 N1
```

The four rules in a) constitute linguistically motivated extensions to G1 but those in b) are harder to justify, indicating that, although 'headedness' can provide useful restrictions on possible rules, it is not the whole story.

For convenience in this experiment we impose the further constraint given below, which restricts rules introducing two preterminals so that the second daughter must always be A0 or N0.

```
CONSTRAINT PT1 :
   [] --> [BAR 0] [BAR 0];
                  N(2)= +.
```

This constraint interacts with HEAD1 to define a further 99 implicit rules not in G1. Many of these rules are linguistically unmotivated. Nevertheless, it may be that the X-bar schema does provide enough constraint, taken together with the CNF constraint and an initial probabilistic bias in favour of the original rules to make, the approach practical and useful. The number of parameters (explicit and implicit rules) in the probabilistic model defined by G1's constraints is of the same order as that used by Lari & Young for the palindrome language. Thus the space of possible analyses remains of similar size, although it is much reduced over the space defined using G1's category set and allowing any possible CNF rule; for instance, for the 14 word sentence *passionately with the sheep the cat chases the ball with the boy so slowly* the implicit grammar provides approximately 380,000 analyses (as V2), whilst the number Catalan(14) $\times\ 11^{14}$ is considerably bigger.

The main motivation for using the inside-outside algorithm and raising the floor of implicit rules is to be able to parse unexpected orderings of terminal categories. Implicit G1 does not quite allow any possible ordering of terminal categories — any sentence ending with an adverb not proceeded by a degree modifier cannot be parsed, for instance. Nevertheless, we can demonstrate that with respect to G1 and one very pervasive form of word order that we will not prevent the system finding a linguistically motivated analysis. The explicit portion of G1 can analyse a) below without modification.

```
a) A girl kisses a boy so passionately
b) A girl so passionately kisses a boy
c) So passionately a girl kisses a boy
d) ? A girl kisses so passionately a boy
e) * A so passionately girl kisses a boy
```

However, b) and c) require the addition of the two implicit rules below:

```
V1 --> A1 V1          V2 --> A1 V2
```

The analysis of d), which is an unlikely but possible example in a stylistically marked context, or of e) which is plain ungrammatical would require the addition of the rules in a) and b) below, respectively:

```
a) V1 --> V0 A1     V1 --> V1 N2
b) N1 --> A1 N1
```

Of course, there are other possible ways, using implicit G1, of parsing these examples and it is an empirical question whether the system will stabilise on these analyses.

4.2 Experiment 1

We generated 500 sentences using a probabilistic version of explicit G1 (probabilities used are given in brackets after the rules in appendix 1). We then produced a probabilistic version of implicit G1 with the implicit rules given a floor probability of around 0.01 and the explicit rules initialised with higher probability. This gave a grammar with a total of 126 CNF CF rules (27 of which were explicit rules derived from G1 PS rules and word declarations). As a simple test we trained this grammar using the inside outside algorithm[1] on the 500 sentences. It was then retrained on an larger corpus, consisting of the original 500 sentences and 28 examples hand-written examples, which could be analysed with the addition of the implicit rules though not the explicit grammar, such as *slowly with the sheep the boy chases the ball.* In this example, an adverb occurs without a degree modifier and both the adverbial and prepositional phrases are preposed. Explicit G1 does not contain rules covering these possibilities. The resulting trained grammar is given in appendix 1 (with rules with zero probability excluded). In Table 1 we give two measures of the entropy (per word) (Wright, 1990) of the source language and the estimated language from the original 500 sentences. For comparison we provide the same measures for the palindrome language investigated by Lari & Young (1990). In the case of the implicit grammar trained on the corpus of 528 sentences, only the entropy of the randomly initialised grammar and the trained grammar are shown, as the entropy of the source language is unknown. These measures are defined by:

$$\begin{aligned} H^{3a} &= -\frac{\sum_K \log P(S)}{\sum_K |S|} \\ H^{3b} &= -\frac{1}{K}\sum_K \frac{\log P(S)}{|S|} \end{aligned}$$

where $P(S)$ and $|S|$ are the probability and length of sentence S respectively and K, the number of sentences in the set. For the extended corpus we show the difference in entropy between the implicit grammar with random probability assignment and the trained grammar. These figures demonstrate that the inside-outside algorithm is converging on a good optimum for modelling both the original language and the extended language given the initial conditions. They also demonstrate that the language being modelled has an entropy / word which is roughly twice that of the palindrome language. Thus we have shown that restricting the space of possible rules that is explored and biasing initial parameters towards a linguistically motivated optimum allows the model to converge very rapidly to a useful solution. In this case, the model converges after only 6 iterations over the training corpus, suggesting that we may be able to extend the

[1] The version of the inside-outside algorithm used throughout this paper is that presented in Jelinek (1985)

Entropy Measure	H^{3a}	H^{3b}
Palindrome Language	0.6870	0.7266
Estimated Panlindrome Lang.	0.6916	0.7504
Explicit Grammar 500	1.5954	1.5688
Implicit Grammar 500	1.5922	1.5690
Initial Grammar 528	2.0979	2.0898
Trained Grammar 528	1.5584	1.5698

Table 1: Measures of Entropy

approach successfully to more complex grammars / languages. Crucially, these results extend to the case where the original explicit grammar is only an approximate (undegenerating) model of the training data. This situation recreates (in a small way) the situation in which the linguistically-motivated grammar available undergenerates with respect to naturally-occurring sentences.

Although these results are promising, we are crucially interested in the analyses assigned by the trained grammar and not in its ability to model the language (strings). One measure of success here is the extent to which the trained grammar has zeroed the parameters for implicit rules. In the final trained version of implicit G1, 52 non-zero rules remain (27 explicit rules + 25 implicit rules). Recall that we said that there are approximately 380,000 analyses for the 14 word sentence *passionately with the sheep the cat chases the ball with the boy so slowly*; this example has 75 parses in the trained grammar. In addition, we analysed 14 sentences parsed using the trained grammar, recording the most probable analysis assigned, the probability of this analysis, the total number of analyses, the probability of all analyses and the likelihood of the analysed sentence given the trained grammar. These sentences are drawn from the original 500, the additional 28 and further unseen examples. Examination of the parse trees shows that the trained grammar is not perfect in the sense that not all the constituents constructed conform to linguistic intuitions; for example, the constituent [N1 [A0 passionately A0] [N1 [DT the DT] [N0 boy N0]N1]N1]. In addition, global ambiguities such as PP attachments are not resolved in a manner which necessarily accords with our lexical semantic intuitions. Nevertheless, the system has done about as well as could be expected given only information about rule frequencies. Furthermore, in the cases where the examples are 'nearly' grammatical, in the sense that they deviate from the explicit grammar by no more than one or two rules, the analyses assigned are almost always the 'closest fit' that can be achieved using a minimal number of implicit rules. In many cases, this results in the linguistically-motivated analysis being induced. The most ambiguous example (17 words long) has 273 parses, the average is just under 60 parses (for average length of 13.5 words). Ignoring PP attachment ambiguity 8 rules are misapplied out of a total of 160 rule applications for these examples, yielding a figure of 95% correct rule application for the examples analysed.

5 Feature-based Encoding of Constraints

In most implementations of X-Bar Theory a feature-based encoding of headedness is assumed and, at least since GPSG (Gazdar et al., 1985), the feature theory is formalised via the unification operation (e.g. Shieber, 1984). Within a broad framework of this type it is possible to envisage imposing many grammatical constraints by treating feature-based generalisations as constraints on the 'compilation' of a (CF) phrase structure grammar (PSG). For example, we could add an agreement constraint to G1 by requiring, for instance, that daughters in rules which have agreement features NUM and PER the values of these features must be consistent, as in AGR below:

```
CONSTRAINT AGR :
    [] --> [NUM, PER], [NUM, PER];
                    NUM(1)=NUM(2),
                    PER(1)=PER(2).
```

This rule blocks the generation of PS rules in which the values of these features differ or, if variable, are not bound. We have extended the ANLT metagrammatical grammar compilation system to incorporate this approach to grammatical constraints or partial grammar specification. In the current ANLT grammar compiler, these rules are used to create a set of 'fleshed out' PS rules in which aliases are expanded out, constraints applied in the form of feature variable or value bindings, and so forth. There are two ways that the compiled out grammar might be interfaced to a system, such as that of Lari & Young (1990), which assumes a CNF CFG.

Firstly, we might expand out PER, NUM and any other features with variable values, creating new rules for all possible values of these features according to the feature declarations. This approach is guaranteed to terminate if feature declarations specify a finite number of values, and the result will be a set of categories which can trivially be replaced by a new set of atomic symbols. However, in general this approach is likely to lead to impractical increases in the size of the grammar for the purposes of tractable re-estimation of probabilities using the inside-outside algorithm and also means that feature-based grammatical constraints can only be employed in a manner which allows compilation into a CFG, precluding the use of category-valued features and other linguistically common techniques which lead to an infinite feature system / category set. Secondly, we can simply re-alias the non-variable parts of categories using the existing aliases (for perspicuity) and filter with the remaining features for the purposes of assigning parses to sentences during the first phase of re-estimation. Alternatively, Briscoe & Carroll (1991) provide an algorithm which automatically constructs the most informative CF backbone from a unification-based grammar in which categories are specified entirely in terms of feature sets. Unification of features could be treated as either a 'hard' constraint to remove certain analyses from the re-estimation process or possibly in a 'softer' fashion to adjust probabilities in a manner sensitive to this phase of the parse process. Currently, we expand the resulting set of feature-based PS rules into a CNF CFG, though we are developing a parsing and re-estimation system which does not require rules in CNF format and can make more direct use of features.

5.1 Experiment 2

The availability of large quantities of tagged and hand-corrected corpora, such as the Penn Treebank, LOB, SEC and others, coupled with the relative reliability of automatic tagging (e.g. de Rose, 1988), means that an obvious test (and potential useful application) for a robust parser would be in the automatic parsing of tag-sequences to construct analyses of the same order of complexity as those currently constructed manually (see above). Most tagged corpora contain between 50-120 distinct lexical tags. These tags most often encode PER and NUM information as well as major category information. We can, therefore, create a lexicon of tags in which each tag is represented as a feature set with determinate values for all features:

```
NNS : [N +, V -, BAR 0, PER 3, NUM Sg].
NNP : [N +, V -, BAR 0, PER 3, NUM Pl]. etc.
```

We have developed a unification-based grammar (G2) for the CLAWS2 tagset (Garside et al., 1987:Appendix B) containing 156 lexical categories (tags), 17 features (maximum number of values 15), 8 non-terminal (aliased) categories, 12 terminal (aliased) categories, 104 binary-branching PS rule (schemata), and 10 constraints of feature propagation and defaulting (of the type described above). These constraints implement headedness, agreement, and also constrain the grammar of coordination via the propagation and defaulting of a feature CONJ. Implicit rules are automatically generated from G2 by creating a new set of CF rules encoding all possible binary rules from the set of aliased categories defined in G2. Then category declarations are used to expand out the aliased categories in these potential implicit rules with their featural definitions. The constraints of G2 are applied to produce bindings and default values in these rules. Any potential implicit rule which does not match the pattern specified by a propagation constraint is filtered out of the set of implicit rules. In this fashion, principles of feature propagation and defaulting are given an absolute interpretation with respect to the generation of the implicit component of the grammar.

We have used G2 to produce explicit and implicit CNF CFGs for use with the inside-outside re-estimation and parsing system. However, were all the features in the PS rules to be expanded out to create a CNF CFG, the resulting explicit grammar would consist of 63,831 rules. Combining these with the implicit rules licensed by the constraints in G2, would generate over 250,000 rules, which is too many for our current implementation and hardware and would also lead to problems of data insufficiency. We chose instead to re-alias a subset of the features in the set of rules produced and form a CNF CFG from these aliases. In this way, we can control the size of the category set to keep the re-estimation technique tractable. In future work, we intend to use the remaining features to filter out some derivations. Thus, we simplified the grammar by not utilising featural distinctions between sub-classes of the major categories, thereby yielding a total of 8271 rules (1850 of which were explicit). This simplification both increased slightly the coverage of the grammar and so too the number of spurious analyses assigned to any given tag sequence. Whilst the simplified explicit grammar parses less than 20% of the SEC, the combined grammar (consisting of both implicit and explicit rules) can assign a complete parse to about 75% of the corpus.

Once again the rules were initialised randomly prior to training, with explicit rules initialised with higher probabilities than implicit rules. After 5 iterations of the inside-outside algorithm, during which very low probability rules were floored to zero, 3786 rules with non-zero probability remained. Using this trained grammar, 14 sentences selected at random from the corpus were analysed, of which 10 were assigned complete parses. The Viterbi algorithm was used to extract the most probable parse, together with its probability and the number of explicit rules employed. Using the inside phase of the inside-outside algorithm, the probability of all analyses of the sentence, the number of analyses and the likelihood of the most probable parse were calculated. Appendix 3 contains a number of these analyses, with a brief comment on the errors associated with the most probable analysis. As can be seen from these examples, approximately 90% of rules used in the most probable parse were explicit rules. This is only to be expected, as these rules are assigned higher probabilities at initialisation. However, it also demonstrates that typically only a few extra rules are necessary in order to modify the grammar to increase coverage. Concerning the errors in the most probable parses: although the grammar is extremely ambiguous, the most probable parse in 8 out of 10 of the complete parses is close to correct, and in the case of observation 7 completely correct. Comparing the most probable analyses with the syntactico-semantic most plausible bracketing and major category assignment yields a correct rule application rate of 79% (39 errors out of 189 applications). Given that about a third of these errors concern level of attachment of arguments / modifiers about which the grammar has no information, these results suggest that the technique is promising. We intend to carry out further tests using extended versions of G2 which do not involve full expansion of the grammar to a CNF CFG.

6 Conclusions

In order to further explore the applicability of the inside-outside algorithm to the robust parsing problem we need to develop a version of the re-estimation and parsing system capable of accepting classes of grammars not restricted to CNF and able to unify features at parse time. In addition, we need to develop a more sophisticated grammar of tag sequences which factors more information into the grammatical constraints used to construct the implicit rules. These steps will, we hope, allow the creation of a parser capable of robust and accurate phrasal-level analysis. In order to extend this analysis to problems such as PP attachment, it would be necessary to incorporate information concerning collocations of semantic classes of words into the probabilistic analyser. However, a robust and accurate phrasal analyser would itself be useful for tasks such as (semi-)automatic acquisition of lexical entries. In the longer term, we hope to merge the techniques we are developing to deal with undergeneration with those we have developed for parse selection for use with the full ANLT grammar (Briscoe & Carroll, 1992).

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Appendix 1 — G1: A simple X-bar Grammar

```
FEATURE N{+, -}
FEATURE V{+, -}
FEATURE BAR{0, 1, 2}
FEATURE MINOR{DT, DG}

ALIAS V2 = [V +, N -, BAR 2].
ALIAS V1 = [V +, N -, BAR 1].
ALIAS V0 = [V +, N -, BAR 0].
ALIAS N1 = [V -, N +, BAR 1].
ALIAS N0 = [V -, N +, BAR 0].
ALIAS P1 = [V -, N -, BAR 1].
ALIAS P0 = [V -, N -, BAR 0].
ALIAS A1 = [V +, N +, BAR 1].
ALIAS A0 = [V +, N +, BAR 0].
ALIAS DT = [MINOR DT].
ALIAS DG = [MINOR DG].

PSRULE S1 : V2 --> N1 V1.   (1.0)
PSRULE VP1 : V1 --> V0 N1.  (0.9)
PSRULE VP2 : V1 --> V1 A1.  (0.1)
PSRULE NP1 : N1 --> DT N0.  (0.8)
PSRULE N1 : N1 --> N1 P1.   (0.2)
PSRULE P1 : P1 --> P0 N1.   (1.0)
PSRULE A1 : A1 --> DT A0.   (1.0)
```

```
WORD cat : N0.              (0.15)
WORD bird : N0.             (0.2)
WORD park : N0.             (0.1)
WORD ball : N0.             (0.2)
WORD girl : N0.             (0.08)
WORD boy : N0.              (0.15)
WORD sheep : N0.            (0.12)
WORD chases : V0.           (0.65)
WORD kisses : V0.           (0.35)
WORD in : P0.               (0.4)
WORD with : P0.             (0.6)
WORD slowly : A0.           (0.72)
WORD passionately : A0.     (0.28)
WORD the : DT               (0.4)
WORD a : DT.                (0.3)
WORD this : DT.             (0.1)
WORD that : DT.             (0.3)
WORD so : DG.               (0.3)
WORD too : DG.              (0.25)
WORD very : DG.             (0.45)
```

Appendix 2 — Probabilistic CNF Trained Version of Implicit G1

V2	-->	V2	P1	0.00057531	implicit
V2	-->	V2	A1	0.00076667	implicit
V2	-->	N1	V1	0.94625349	explicit
V2	-->	N0	V1	0.00541748	implicit
V2	-->	P1	V2	0.00693598	implicit
V2	-->	A1	V2	0.02500444	implicit
V2	-->	A0	V2	0.01504663	implicit
V1	-->	V1	P1	0.00050115	implicit
V1	-->	V1	A1	0.07906031	explicit
V1	-->	V0	N1	0.90583286	explicit
V1	-->	V0	P1	0.00171885	implicit
V1	-->	P1	V1	0.00606044	implicit
V1	-->	A1	V1	0.00166985	implicit
V1	-->	A0	V1	0.00515654	implicit
V0	-->	chases	#	0.71401515	explicit
V0	-->	kisses	#	0.28598485	explicit
N1	-->	N1	P1	0.17184879	explicit
N1	-->	N1	A1	0.00003595	implicit
N1	-->	N0	A1	0.00060919	implicit
N1	-->	P1	N1	0.00074166	implicit
N1	-->	A1	N1	0.00085517	implicit
N1	-->	A0	N1	0.00166976	implicit
N1	-->	DT	N0	0.82423948	explicit
N0	-->	cat	#	0.16212233	explicit
N0	-->	bird	#	0.19528371	explicit
N0	-->	park	#	0.09874724	explicit
N0	-->	ball	#	0.21075903	explicit
N0	-->	girl	#	0.08032424	explicit
N0	-->	boy	#	0.15401621	explicit
N0	-->	sheep	#	0.09874724	explicit

```
P1   -->   V1          P1          0.00328333 implicit
P1   -->   P1          P1          0.00099618 implicit
P1   -->   P0          N1          0.99571773 explicit
P1   -->   A0          P1          0.00000276 implicit
P0   -->   in          #           0.44554455 explicit
P0   -->   with        #           0.55445545 explicit
A1   -->   V1          A1          0.00001139 implicit
A1   -->   P1          A1          0.03045650 implicit
A1   -->   A1          P1          0.00592188 implicit
A1   -->   A1          A1          0.03028750 implicit
A1   -->   A0          P1          0.11100389 implicit
A1   -->   A0          A1          0.00120497 implicit
A1   -->   DG          A0          0.82111386 explicit
A0   -->   slowly      #           0.66250000 explicit
A0   -->   passionately #          0.33750000 explicit
DG   -->   so          #           0.27586207 explicit
DG   -->   too         #           0.27586207 explicit
DG   -->   very        #           0.44827586 explicit
DT   -->   the         #           0.43754619 explicit
DT   -->   a           #           0.29120473 explicit
DT   -->   this        #           0.09460458 explicit
DT   -->   that        #           0.17664449 explicit
```

Appendix 3 — SEC Parses with G2

```
A) Complete Parses
-------------------------------------------------------------------------
Observation 1

Next_MD week_NNT1 a_AT1 delegation_NN1 of_IO nine_MC Protestant_JJ
ministers_NNS2 from_II Argentina_NP1 visits_VVZ the_AT Autumn_NN1
assembly_NN1 of_IO the_AT British_JJ Council_NNJ of_IO Churches_NNJ2

Parsed sentence:
[V2.2
  [N2.2
   [N1.4 [A0.1 Next_MD A0.1][N0.2 week_NNT1 N0.2]N1.4]
   [N2.2
    [DT.4 a_AT1 DT.4]
    [N1.4 [N1.4 [N0.2 delegation_NN1 N0.2]
                [P1.2 [P0.7 of_IO P0.7]
                      [N2.7
                        [DT.3 nine_MC DT.3]
                        [N1.2 [A1.1 Protestant_JJ A1.1]
                           [N0.1 ministers_NNS2 N0.1]N1.2]N2.7]P1.2]N1.4]
          [P1.2 [P0.7 from_II P0.7]
                [N2.2 Argentina_NP1 N2.2]P1.2]N1.4]N2.2]N2.2
  [V1.2 [V0.13 visits_VVZ V0.13]
        [N2.2 [DT.4 the_AT DT.4]
              [N1.4 [N0.2 [N0.2 Autumn_NN1 N0.2][N0.2 assembly_NN1 N0.2]N0.2]
                    [P1.2 [P0.7 of_IO P0.7]
                          [N2.2 [DT.4 the_AT DT.4]
                                [N1.4 [A1.1 British_JJ A1.1]
                                      [N1.4 [N0.2 Council_NNJ N0.2]
                                            [P1.2 [P0.5 of_IO P0.5]
                                                  [N2.1 Churches_NNJ2 N2.1]
                                P1.2]N1.4]N1.4]N2.2]P1.2]N1.4]N2.2]V1.2]V2.2]

Sentence length: 19 words
best 5.809595e-33 all 1.064649e-30 likelihood   0.005457
```

(Tot number of parses : 21862499278031036)

Total Rules Applied 40 Total Explicit 36 (90.00%)
Ratio of correct rules / rules applied: 18/19

Comments: 'Next week' not part of N2 but V2; 'from Argentina' attach lower?

Observation 2

More_DAR news_NN1 about_II the_AT Reverend_NNS1 Sun_NP1 Myung_NP1
Moon_NP1 founder_NN1 of_IO the_AT Unification_NN1 church_NN1 who_PNQS
's_VBZ currently_RR in_II jail_NN1 for_IF tax_NN1 evasion_NN1

Parsed sentence:

```
[V2.2
  [N2.2
   [N1.4
    [A1.2
     [A0.2 More_DAR A0.2]
     [N1.4 [N0.2 news_NN1 N0.2]
           [P1.2 [P0.7 about_II P0.7]
                 [N2.2
                   [DT.4 the_AT DT.4]
                   [N1.4
                    [N0.2
                     [N0.2
                      [N0.2
                       [N0.2 [N0.2 Reverend_NNS1 N0.2] [N0.2 Sun_NP1 N0.2]N0.2]
                       [N0.2 Myung_NP1 N0.2]N0.2]
                      [N0.2 Moon_NP1 N0.2]N0.2]
                     [N0.2 founder_NN1 N0.2]N0.2]
                    [P1.2 [P0.7 of_IO P0.7]
                          [N2.2 [DT.4 the_AT DT.4]
                                [N0.2 Unification_NN1 N0.2]N2.2]P1.2
                                              ]N1.4]N2.2]P1.2]N1.4]A1.2]
    [N0.2 church_NN1 N0.2]N1.4]
   [N2.4 who_PNQS N2.4] N2.2]
  [V1.2 [V0.3 's_VBZ V0.3]
     [P2.1 [A1.4 currently_RR A1.4]
           [P1.2 [P0.7 in_II P0.7]
                 [N2.2 [N1.4 [N0.2 jail_NN1 N0.2]
                             [P1.2 [P0.8 for_IF P0.8]
                                   [N0.2 tax_NN1 N0.2]P1.2]N1.4]
                       [N0.2 evasion_NN1 N0.2]N2.2]P1.2]P2.1]V1.2]V2.2]
```

Sentence length: 21 words
best 8.557940e-33 all 1.232113e-29 likelihood 0.000695
(Tot number of parses : 31241634778345856)

Total Rules Applied 42 Total Explicit Rules Applied 38 (90.48 %)
Ratio of correct rules / rules applied: 14/20

Comments: 'more' not head; 'founder' not part of name; 'unif church' split; 'currently' not in PP, 'tax evasion' split; N2 --> N1 N0 = too probable implicit rule; relative clause split

---

Observation 3

he_PPHS1 was_VBDZ awarded_VVN an_AT1 honorary_JJ degree_NN1 last_MD

```
week_NNT1 by_II the_AT Roman_JJ Catholic_JJ University_NNL1 of_IO
la_&FW Plata_NP1 in_II Buenos_NP1 Aires_NP1 Argentina_NP1

Parsed sentence:
[V2.2
 [N2.2 he_PPHS1 N2.2]
 [V1.2
  [V1.2 [V0.3 was_VBDZ V0.3]
   [V1.1 [V0.12 awarded_VVN V0.12]
   [N2.2 [DT.4 an_AT1 DT.4]
         [N1.4 [A1.1 honorary_JJ A1.1][N0.2 degree_NN1 N0.2]N1.4]N2.2]V1.1]V1.2]
  [N2.4 [N1.4 [A1.1 [A0.1 last_MD A0.1]
              [N1.4 [N0.2 week_NNT1 N0.2]
                    [P1.2 [P0.7 by_II P0.7]
                          [N2.2
                            [DT.4 the_AT DT.4]
                            [N1.4 [A1.1 Roman_JJ A1.1]
                             [N1.4
                              [A1.1 Catholic_JJ A1.1]
                              [N1.4 [N0.2 University_NNL1 N0.2]
                                    [P1.2 [P0.7 of_IO P0.7]
                                    [N2.2 la_&FW N2.2]P1.2]N1.4]N1.4]N1.4]
                                                      N2.2]P1.2]N1.4]A1.1]
                             [N1.4 [N0.2 Plata_NP1 N0.2]
                                   [P1.2 [P0.7 in_II P0.7]
                                         [N2.2 Buenos_NP1 N2.2]P1.2]N1.4]N1.4]
        [N0.2 [N0.2 Aires_NP1 N0.2][N0.2 Argentina_NP1 N0.2] N0.2]
                                                       N2.4]V1.2]V2.2]

Sentence length: 20 words
best 1.449373e-30 all 2.667054e-27 likelihood   0.000543
(Tot number of parses : 21272983202438840 )

Total Rules Applied 40  Total Explicit Rules Applied 38 ( 95.00 % )
Ratio of correct rules / rules applied: 16/19

Comments: 'last week' not postmodified by 'by...'; 'la Plata' split;
'Buenos Aires' split

-----------------------------------------------------------------
Observation 4

In_II announcing_VVG the_AT award_NN1 in_II New_NP1 York_NP1 the_AT
rector_NNS1 of_IO the_AT university_NNL1 Dr_NNSB1 Nicholas_NP1
Argentato_NP1 described_VVD Mr_NNSB1 Moon_NP1 as_II a_AT1 prophet_NN1
of_IO our_APP$ time_NN1

Parsed sentence:
[V2.2
 [P1.2 [P0.3 In_II P0.3]
       [V2.1 [V1.1 [V0.12 announcing_VVG V0.12]
                   [N2.2 [DT.4 the_AT DT.4]
                         [N1.4 [N0.2 award_NN1 N0.2]
                               [P1.2 [P0.7 in_II P0.7]
                                     [N2.2 New_NP1 N2.2]P1.2]N1.4]N2.2]V1.1]
             [N0.2 York_NP1 N0.2]V2.1]P1.2]
 [V2.2
   [N2.2 [DT.4 the_AT DT.4]
         [N1.4 [N0.2 rector_NNS1 N0.2]
               [P1.2 [P0.7 of_IO P0.7]
                     [N2.2 [DT.4 the_AT DT.4
```

```
                          [N0.2
                           [N0.2
                            [N0.2 [N0.2 university_NNL1 N0.2]
                                  [N0.2 Dr_NNSB1 N0.2]N0.2]
                           [N0.2 Nicholas_NP1 N0.2]N0.2]
                          [N0.2 Argentato_NP1 N0.2]N0.2]N2.2]P1.2]N1.4]N2.2]
   [V1.2 [V0.13 described_VVD V0.13]
         [N2.2
          [N1.4
           [N0.2 [N0.2 Mr_NNSB1 N0.2][N0.2 Moon_NP1 N0.2]N0.2]
           [P1.2 [P0.7 as_II P0.7]
                 [N2.2 [DT.4 a_AT1 DT.4]
                       [N1.4 [N0.2 prophet_NN1 N0.2]
                             [P1.2 [P0.7 of_IO P0.7]
                                   [DT.1 our_APP$ DT.1]P1.2]N1.4]N2.2]
                                                               P1.2]N1.4]
          [N0.2 time_NN1 N0.2]N2.2]V1.2]V2.2]V2.2]

Sentence length: 24 words
best 3.608663e-38 all 4.044410e-35 likelihood   0.000892
(Tot number of parses : 9194955556291413934080 )

Total Rules Applied 48  Total Explicit Rules Applied 46 ( 95.83 % )
Ratio of correct rules / rules applied: 18/23

Comments: 'New York' split; no parenthetical for 'Dr..'; 'as...' too low;
'our time' split; 'of our' P1 --> P0 DT

----------------------------------------------------------------------------
Observation 7

The_AT assembly_NN1 will_VM also_RR be_VB0 discussing_VVG the_AT
UK_NP1 immigration_NN1 laws_NN2 Hong_NP1 Kong_NP1 teenagers_NN2 in_II
the_AT church_NN1 and_CC of_RR21 church_NN1 unity_NN1 schemes_NN2

Parsed sentence:
[V2.2
 [N2.2 [DT.4 The_AT DT.4][N0.2 assembly_NN1 N0.2]N2.2]
 [V1.2 [V0.9 will_VM V0.9]
       [V1.1 [A1.4 also_RR A1.4]
             [V1.1 [V0.2 be_VB0 V0.2]
                   [V1.1 [V0.12 discussing_VVG V0.12]
                         [N2.7
                          [N2.1 [DT.3 the_AT DT.3]
                                [N1.2 [N0.2 [N0.2 UK_NP1 N0.2]
                                            [N0.2 immigration_NN1 N0.2]N0.2]
                                      [N0.1 laws_NN2 N0.1]N1.2]N2.1]
                          [N2.12
                           [N2.7
                            [N0.2 [N0.2 Hong_NP1 N0.2][N0.2 Kong_NP1 N0.2]N0.2]
                            [N1.2 [N0.1 teenagers_NN2 N0.1]
                                  [P1.2 [P0.7 in_II P0.7]
                                        [N2.2
                                          [DT.4 the_AT DT.4]
                                          [N0.2 church_NN1 N0.2]N2.2]P1.2]N1.2]N2.7]
                           [N2.12
                            [CJ.1 and_CC CJ.1]
                            [N2.7 [A0.4 of_RR21 A0.4]
                                  [N1.2 [N0.2 [N0.2 church_NN1 N0.2]
                                              [N0.2 unity_NN1 N0.2]N0.2]
                                        [N0.1 schemes_NN2 N0.1]N1.2] N2.7] N2.12]N2.12]
```

```
                                          N2.7]V1.1]V1.1]V1.1]V1.2]V2.2]
```

Sentence length: 21 words
best 2.152796e-31 all 3.042978e-28 likelihood   0.000707
(Tot number of parses : 1032440449833788)

Total Rules Applied 42 Tot. Explicit Rules 38 (90.48 %)
Ratio of correct rules / rules applied: 20/20

Comments: correct

Observation 9

Parsed sentence:

More_RGR important_JJ however_RR is_VBZ that_CST the_AT biblical_JJ
writers_NN2 themselves_PPX2 thought_VVD that_CST events_NN2 that_CST
followed_VVD natural_JJ laws_NN2 could_VM still_RR be_VB0 regarded_VVN
as_CSA miraculous_JJ

Parsed sentence:

```
[P2.1
 [A2.5
  [A2.2 [A1.5 More_RGR A1.5][A1.1 important_JJ A1.1]A2.2]
  [A1.4 [A0.4 however_RR A0.4]
        [V1.2 [V0.3 is_VBZ V0.3]
              [P1.2 [P0.3 that_CST P0.3]
                    [V2.1
                      [N2.1 [DT.3 the_AT DT.3]
                            [N1.2 [A1.1 biblical_JJ A1.1]
                                  [N0.1 writers_NN2 N0.1] N1.2] N2.1]
                      [V1.1 [N2.1 themselves_PPX2 N2.1]
                            [V0.12 thought_VVD V0.12] V1.1] V2.1] P1.2] V1.2] A1.4] A2.5]
 [P1.2 [P0.3 that_CST P0.3]
       [N1.2 [N0.1 events_NN2 N0.1]
             [P1.2 [P0.3 that_CST P0.3]
                   [V2.1 [N2.7 [V0.13 followed_VVD V0.13]
                               [N1.2 [A1.1 natural_JJ A1.1]
                                     [N0.1 laws_NN2 N0.1] N1.2] N2.7]
                         [V2.5 [V0.8 could_VM V0.8]
                               [V2.1 [A0.4 still_RR A0.4]
                                     [V1.1
                                       [V1.1 [V0.2 be_VB0 V0.2]
                                             [V1.1 [V0.12 regarded_VVN V0.12]
                                                   [P0.8 as_CSA P0.8] V1.1] V1.1]
                                       [A1.1 miraculous_JJ A1.1] V1.1] V2.1] V2.5]
                                                    V2.1] P1.2] N1.2] P1.2] P2.1]
```

Sentence length: 22 words
best 2.047509e-41 all 3.249200e-38 likelihood   0.000630
(Tot number of parses : 2341100946234064)

Total Rules Applied 44 Total Explicit 38 (86.36%)
Ratio of correct rules / rules applied: 14/21

Comments: root P2; 'themselves thought' joined; 'thought that' split;
'as miraculous' split; rel clause not P1 + subj gap; 'still be' not V2
(explicit grammar very inadequate for this e.g.)