

Chapter 14

Statistical Parsing

*Two roads diverged in a wood, and I –
I took the one less traveled by...*
Robert Frost, *The Road Not Taken*

The characters in Damon Runyon’s short stories are willing to bet “on any proposition whatever”, as Runyon says about Sky Masterson in *The Idyll of Miss Sarah Brown*, from the probability of getting aces back-to-back to the odds against a man being able to throw a peanut from second base to home plate. There is a moral here for language processing: with enough knowledge we can figure the probability of just about anything. The last two chapters have introduced sophisticated models of syntactic structure and its parsing. In this chapter we show that it is possible to build probabilistic models of syntactic knowledge and use some of this probabilistic knowledge in efficient probabilistic parsers.

One crucial use of probabilistic parsing is to solve the problem of **disambiguation**. Recall from Chapter 13 that sentences on average tend to be syntactically ambiguous because of problems like **coordination ambiguity** and **attachment ambiguity**. The CKY and Earley parsing algorithms could represent these ambiguities in an efficient way but were not equipped to resolve them. A probabilistic parser offers a solution to the problem: compute the probability of each interpretation and choose the most probable interpretation. Thus, due to the prevalence of ambiguity, most modern parsers used for natural language understanding tasks (thematic role labeling, summarization, question-answering, machine translation) are of necessity probabilistic.

Another important use of probabilistic grammars and parsers is in **language modeling** for speech recognition. We saw that N -gram grammars are used in speech recognizers to predict upcoming words, helping constrain the acoustic model search for words. Probabilistic versions of more sophisticated grammars can provide additional predictive power to a speech recognizer. Of course, humans have to deal with the same problems of ambiguity as do speech recognizers, and it is interesting that psychological experiments suggest that people use something like these probabilistic grammars in human language processing tasks (e.g., human reading or speech understanding).

The most commonly used probabilistic grammar is the **probabilistic context-free grammar** (PCFG), a probabilistic augmentation of context-free grammars in which each rule is associated with a probability. We introduce PCFGs in the next section, showing how they can be trained on a hand-labeled Treebank grammar and how they can be parsed. We present the most basic parsing algorithm for PCFGs, which is the probabilistic version of the **CKY algorithm** that we saw in Chapter 13.

We then show a number of ways that we can improve on this basic probability model (PCFGs trained on Treebank grammars). One method of improving a trained

Trebank grammar is to change the names of the non-terminals. By making the non-terminals sometimes more specific and sometimes more general, we can come up with a grammar with a better probability model that leads to improved parsing scores. Another augmentation of the PCFG works by adding more sophisticated conditioning factors, extending PCFGs to handle probabilistic **subcategorization** information and probabilistic **lexical dependencies**.

Finally, we describe the standard PARSEVAL metrics for evaluating parsers and discuss some psychological results on human parsing.

14.1 Probabilistic Context-Free Grammars

PCFG
SCFG

The simplest augmentation of the context-free grammar is the **Probabilistic Context-Free Grammar (PCFG)**, also known as the **Stochastic Context-Free Grammar (SCFG)**, first proposed by Booth (1969). Recall that a context-free grammar G is defined by four parameters (N, Σ, R, S) ; a probabilistic context-free grammar is also defined by four parameters, with a slight augmentation to each of the rules in R :

N a set of **non-terminal symbols** (or **variables**)
 Σ a set of **terminal symbols** (disjoint from N)
 R a set of **rules** or productions, each of the form $A \rightarrow \beta [p]$,
 where A is a non-terminal,
 β is a string of symbols from the infinite set of strings $(\Sigma \cup N)^*$,
 and p is a number between 0 and 1 expressing $P(\beta|A)$
 S a designated **start symbol**

That is, a PCFG differs from a standard CFG by augmenting each rule in R with a conditional probability:

$$A \rightarrow \beta [p] \quad (14.1)$$

Here p expresses the probability that the given non-terminal A will be expanded to the sequence β . That is, p is the conditional probability of a given expansion β given the left-hand-side (LHS) non-terminal A . We can represent this probability as

$$P(A \rightarrow \beta)$$

or as

$$P(A \rightarrow \beta|A)$$

or as

$$P(RHS|LHS)$$

Thus, if we consider all the possible expansions of a non-terminal, the sum of their probabilities must be 1:

$$\sum_{\beta} P(A \rightarrow \beta) = 1$$

Grammar		Lexicon	
$S \rightarrow NP VP$	[.80]	$Det \rightarrow that$ [.10] | a [.30] | the [.60]	
$S \rightarrow Aux NP VP$	[.15]	$Noun \rightarrow book$ [.10] | $flight$ [.30]	
$S \rightarrow VP$	[.05]	| $meal$ [.15] | $money$ [.05]	
$NP \rightarrow Pronoun$	[.35]	| $flights$ [.40] | $dinner$ [.10]	
$NP \rightarrow Proper-Noun$	[.30]	$Verb \rightarrow book$ [.30] | $include$ [.30]	
$NP \rightarrow Det Nominal$	[.20]	| $prefer$ [.40]	
$NP \rightarrow Nominal$	[.15]	$Pronoun \rightarrow I$ [.40] | she [.05]	
$Nominal \rightarrow Noun$	[.75]	| me [.15] | you [.40]	
$Nominal \rightarrow Nominal Noun$	[.20]	$Proper-Noun \rightarrow Houston$ [.60]	
$Nominal \rightarrow Nominal PP$	[.05]	| NWA [.40]	
$VP \rightarrow Verb$	[.35]	$Aux \rightarrow does$ [.60] | can [.40]	
$VP \rightarrow Verb NP$	[.20]	$Preposition \rightarrow from$ [.30] | to [.30]	
$VP \rightarrow Verb NP PP$	[.10]	| on [.20] | $near$ [.15]	
$VP \rightarrow Verb PP$	[.15]	| $through$ [.05]	
$VP \rightarrow Verb NP NP$	[.05]		
$VP \rightarrow VP PP$	[.15]		
$PP \rightarrow Preposition NP$	[1.0]		

Figure 14.1 A PCFG that is a probabilistic augmentation of the \mathcal{L}_1 miniature English CFG grammar and lexicon of Fig. ???. These probabilities were made up for pedagogical purposes and are not based on a corpus (since any real corpus would have many more rules, so the true probabilities of each rule would be much smaller).

Figure 14.1 shows a PCFG: a probabilistic augmentation of the \mathcal{L}_1 miniature English CFG grammar and lexicon. Note that the probabilities of all of the expansions of each non-terminal sum to 1. Also note that these probabilities were made up for pedagogical purposes. A real grammar has a great many more rules for each non-terminal; hence, the probabilities of any particular rule would tend to be much smaller.

Consistent

A PCFG is said to be **consistent** if the sum of the probabilities of all sentences in the language equals 1. Certain kinds of recursive rules cause a grammar to be inconsistent by causing infinitely looping derivations for some sentences. For example, a rule $S \rightarrow S$ with probability 1 would lead to lost probability mass due to derivations that never terminate. See Booth and Thompson (1973) for more details on consistent and inconsistent grammars.

How are PCFGs used? A PCFG can be used to estimate a number of useful probabilities concerning a sentence and its parse tree(s), including the probability of a particular parse tree (useful in disambiguation) and the probability of a sentence or a piece of a sentence (useful in language modeling). Let's see how this works.

14.1.1 PCFGs for Disambiguation

A PCFG assigns a probability to each parse tree T (i.e., each **derivation**) of a sentence S . This attribute is useful in **disambiguation**. For example, consider the two parses of the sentence “Book the dinner flight” shown in Fig. 14.2. The sensible parse on the left means “Book a flight that serves dinner”. The nonsensical parse on the right, however, would have to mean something like “Book a flight on behalf of ‘the dinner’” just as a

structurally similar sentence like “Can you book John a flight?” means something like “Can you book a flight on behalf of John?”

The probability of a particular parse T is defined as the product of the probabilities of all the n rules used to expand each of the n non-terminal nodes in the parse tree T , where each rule i can be expressed as $LHS_i \rightarrow RHS_i$:

$$P(T, S) = \prod_{i=1}^n P(RHS_i | LHS_i) \quad (14.2)$$

The resulting probability $P(T, S)$ is both the joint probability of the parse and the sentence and also the probability of the parse $P(T)$. How can this be true? First, by the definition of joint probability:

$$P(T, S) = P(T)P(S|T) \quad (14.3)$$

But since a parse tree includes all the words of the sentence, $P(S|T)$ is 1. Thus,

$$P(T, S) = P(T)P(S|T) = P(T) \quad (14.4)$$

We can compute the probability of each of the trees in Fig. 14.2 by multiplying the probabilities of each of the rules used in the derivation. For example, the probability of the left tree in Fig. 14.2a (call it T_{left}) and the right tree (Fig. 14.2b or T_{right}) can be computed as follows:

$$\begin{aligned} P(T_{left}) &= .05 * .20 * .20 * .20 * .75 * .30 * .60 * .10 * .40 = 2.2 \times 10^{-6} \\ P(T_{right}) &= .05 * .10 * .20 * .15 * .75 * .75 * .30 * .60 * .10 * .40 = 6.1 \times 10^{-7} \end{aligned}$$

We can see that the left (transitive) tree in Fig. 14.2 has a much higher probability than the ditransitive tree on the right. Thus, this parse would correctly be chosen by a disambiguation algorithm that selects the parse with the highest PCFG probability.

Let's formalize this intuition that picking the parse with the highest probability is the correct way to do disambiguation. Consider all the possible parse trees for a given sentence S . The string of words S is called the **yield** of any parse tree over S . Thus, out of all parse trees with a yield of S , the disambiguation algorithm picks the parse tree that is most probable given S :

$$\hat{T}(S) = \underset{T \text{ s.t. } S = \text{yield}(T)}{\operatorname{argmax}} P(T|S) \quad (14.5)$$

By definition, the probability $P(T|S)$ can be rewritten as $P(T, S)/P(S)$, thus leading to

$$\hat{T}(S) = \underset{T \text{ s.t. } S = \text{yield}(T)}{\operatorname{argmax}} \frac{P(T, S)}{P(S)} \quad (14.6)$$

Since we are maximizing over all parse trees for the same sentence, $P(S)$ will be a constant for each tree, so we can eliminate it:

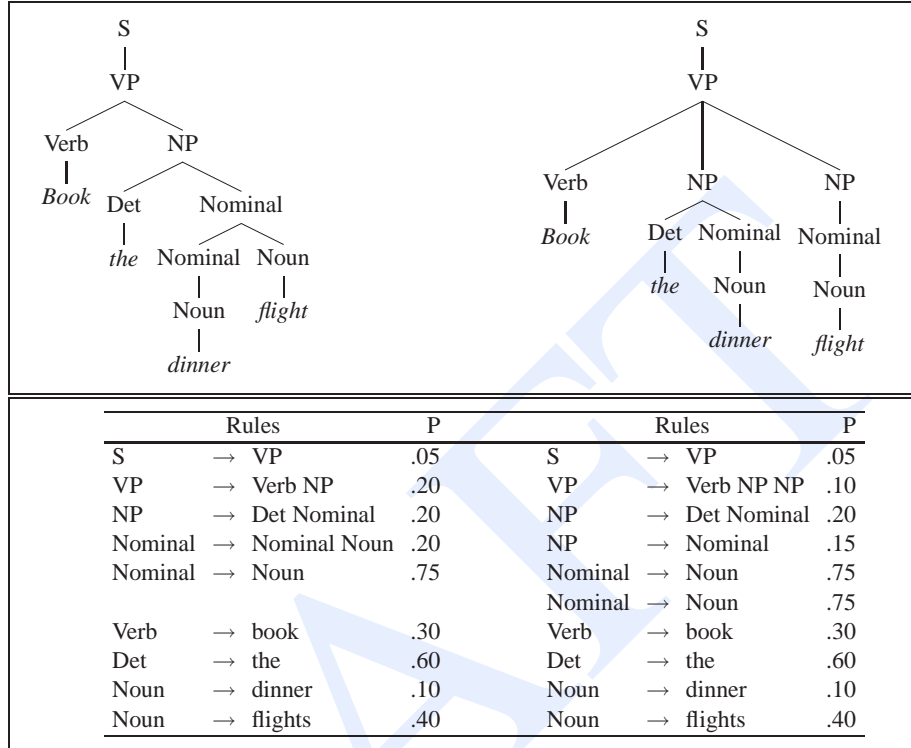


Figure 14.2 Two parse trees for an ambiguous sentence. The transitive parse on the left corresponds to the sensible meaning “Book a flight that serves dinner”, while the ditransitive parse on the right corresponds to the nonsensical meaning “Book a flight on behalf of ‘the dinner’”.

$$\hat{T}(S) = \operatorname{argmax}_{T \text{ s.t. } S = \text{yield}(T)} P(T, S) \quad (14.7)$$

Furthermore, since we showed above that $P(T, S) = P(T)$, the final equation for choosing the most likely parse neatly simplifies to choosing the parse with the highest probability:

$$\hat{T}(S) = \operatorname{argmax}_{T \text{ s.t. } S = \text{yield}(T)} P(T) \quad (14.8)$$

14.1.2 PCFGs for Language Modeling

A second attribute of a PCFG is that it assigns a probability to the string of words constituting a sentence. This is important in **language modeling**, whether for use in speech recognition, machine translation, spelling correction, augmentative communication, or other applications. The probability of an unambiguous sentence is $P(T, S) = P(T)$ or just the probability of the single parse tree for that sentence. The probability of an ambiguous sentence is the sum of the probabilities of all the parse trees for the sentence:

$$P(S) = \sum_{T \text{ s.t. } S = \text{yield}(T)} P(T, S) \quad (14.9)$$

$$= \sum_{T \text{ s.t. } S = \text{yield}(T)} P(T) \quad (14.10)$$

An additional feature of PCFGs that is useful for language modeling is their ability to assign a probability to substrings of a sentence. For example, suppose we want to know the probability of the next word w_i in a sentence given all the words we've seen so far w_1, \dots, w_{i-1} . The general formula for this is

$$P(w_i | w_1, w_2, \dots, w_{i-1}) = \frac{P(w_1, w_2, \dots, w_{i-1}, w_i, \dots)}{P(w_1, w_2, \dots, w_{i-1}, \dots)} \quad (14.11)$$

We saw in Chapter 4 a simple approximation of this probability using N -grams, conditioning on only the last word or two instead of the entire context; thus, the **bigram approximation** would give us

$$P(w_i | w_1, w_2, \dots, w_{i-1}) \approx \frac{P(w_{i-1}, w_i)}{P(w_{i-1})} \quad (14.12)$$

But the fact that the N -gram model can only make use of a couple words of context means it is ignoring potentially useful prediction cues. Consider predicting the word *after* in the following sentence from Chelba and Jelinek (2000):

(14.13) the contract ended with a loss of 7 cents after trading as low as 9 cents

A trigram grammar must predict *after* from the words *7 cents*, while it seems clear that the verb *ended* and the subject *contract* would be useful predictors that a PCFG-based parser could help us make use of. Indeed, it turns out that PCFGs allow us to condition on the entire previous context w_1, w_2, \dots, w_{i-1} shown in Eq. 14.11. We discuss the details of ways to use PCFGs and augmentations of PCFGs as language models in Section 14.9.

In summary, this section and the previous one have shown that PCFGs can be applied both to disambiguation in syntactic parsing and to word prediction in language modeling. Both of these applications require that we be able to compute the probability of parse tree T for a given sentence S . The next few sections introduce some algorithms for computing this probability.

14.2 Probabilistic CKY Parsing of PCFGs

The parsing problem for PCFGs is to produce the most-likely parse \hat{T} for a given sentence S , that is,

$$\hat{T}(S) = \operatorname{argmax}_{T \text{ s.t. } S = \text{yield}(T)} P(T) \quad (14.14)$$

The algorithms for computing the most likely parse are simple extensions of the standard algorithms for parsing; there are probabilistic versions of both the CKY and Earley algorithms of Chapter 13. Most modern probabilistic parsers are based on the **probabilistic CKY** algorithm, first described by Ney (1991).

As with the CKY algorithm, we assume for the probabilistic CKY algorithm that the PCFG is in Chomsky normal form. Recall from page ?? that grammars in CNF are restricted to rules of the form $A \rightarrow BC$, or $A \rightarrow w$. That is, the right-hand side of each rule must expand to either two non-terminals or to a single terminal.

For the CKY algorithm, we represented each sentence as having indices between the words. Thus, an example sentence like

(14.15) Book the flight through Houston.

would assume the following indices between each word:

(14.16) ① Book ② the ③ flight ④ through ⑤ Houston ⑥

Using these indices, each constituent in the CKY parse tree is encoded in a two-dimensional matrix. Specifically, for a sentence of length n and a grammar that contains V non-terminals, we use the upper-triangular portion of an $(n+1) \times (n+1)$ matrix. For CKY, each cell $table[i, j]$ contained a list of constituents that could span the sequence of words from i to j . For probabilistic CKY, it's slightly simpler to think of the constituents in each cell as constituting a third dimension of maximum length V . This third dimension corresponds to each non-terminal that can be placed in this cell, and the value of the cell is then a probability for that non-terminal/constituent rather than a list of constituents. In summary, each cell $[i, j, A]$ in this $(n+1) \times (n+1) \times V$ matrix is the probability of a constituent A that spans positions i through j of the input.

Figure 14.3 gives pseudocode for this probabilistic CKY algorithm, extending the basic CKY algorithm from Fig. ??.

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function PROBABILISTIC-CKY(words, grammar) returns most probable parse
                                                    and its probability

for  $j \leftarrow$  from 1 to LENGTH(words) do
  for all  $\{ A \mid A \rightarrow words[j] \in grammar \}$ 
     $table[j-1, j, A] \leftarrow P(A \rightarrow words[j])$ 
  for  $i \leftarrow$  from  $j-2$  downto 0 do
    for  $k \leftarrow i+1$  to  $j-1$  do
      for all  $\{ A \mid A \rightarrow BC \in grammar,$ 
        and  $table[i, k, B] > 0$  and  $table[k, j, C] > 0 \}$ 
        if  $(table[i, j, A] < P(A \rightarrow BC) \times table[i, k, B] \times table[k, j, C])$  then
           $table[i, j, A] \leftarrow P(A \rightarrow BC) \times table[i, k, B] \times table[k, j, C]$ 
           $back[i, j, A] \leftarrow \{k, B, C\}$ 
  return BUILD_TREE(back[1, LENGTH(words), S], table[1, LENGTH(words), S])

```

Figure 14.3 The probabilistic CKY algorithm for finding the maximum probability parse of a string of num_words words given a PCFG grammar with num_rules rules in Chomsky normal form. *back* is an array of backpointers used to recover the best parse. The *build_tree* function is left as an exercise to the reader.

Like the CKY algorithm, the probabilistic CKY algorithm as shown in Fig. 14.3 requires a grammar in Chomsky normal form. Converting a probabilistic grammar to CNF requires that we also modify the probabilities so that the probability of each parse remains the same under the new CNF grammar. Exercise 14.2 asks you to modify the algorithm for conversion to CNF in Chapter 13 so that it correctly handles rule probabilities.

In practice, we more often use a generalized CKY algorithm that handles unit productions directly rather than converting them to CNF. Recall that Exercise 13.3 asked you to make this change in CKY; Exercise 14.3 asks you to extend this change to probabilistic CKY.

Let's see an example of the probabilistic CKY chart, using the following mini-grammar, which is already in CNF:

$S \rightarrow NP VP$	.80	$Det \rightarrow the$	.40
$NP \rightarrow Det N$	.30	$Det \rightarrow a$	.40
$VP \rightarrow V NP$	.20	$N \rightarrow meal$	.01
$V \rightarrow includes$	.05	$N \rightarrow flight$	.02

Given this grammar, Fig. 14.4 shows the first steps in the probabilistic CKY parse of this sentence:

(14.17) The flight includes a meal

Det: .40 [0,1]	NP: $.30 * .40 * .02$ = .0024 [0,2]	[0,3]	[0,4]	[0,5]
	N: .02 [1,2]	[1,3]	[1,4]	[1,5]
		V: .05 [2,3]	[2,4]	[3,5]
			[3,4]	[3,5]
				[4,5]
The	flight	includes	a	meal

Figure 14.4 The beginning of the probabilistic CKY matrix. Filling out the rest of the chart is left as Exercise 14.4 for the reader.

14.3 Ways to Learn PCFG Rule Probabilities

Where do PCFG rule probabilities come from? There are two ways to learn probabilities for the rules of a grammar. The simplest way is to use a *treebank*, a corpus of already parsed sentences. Recall that we introduced in Chapter 12 the idea of treebanks and the commonly used **Penn Treebank** (Marcus et al., 1993), a collection of parse trees in English, Chinese, and other languages that is distributed by the Linguistic Data Consortium. Given a treebank, we can compute the probability of each expansion of a non-terminal by counting the number of times that expansion occurs and then normalizing.

$$P(\alpha \rightarrow \beta | \alpha) = \frac{\text{Count}(\alpha \rightarrow \beta)}{\sum_{\gamma} \text{Count}(\alpha \rightarrow \gamma)} = \frac{\text{Count}(\alpha \rightarrow \beta)}{\text{Count}(\alpha)} \quad (14.18)$$

If we don't have a treebank but we do have a (non-probabilistic) parser, we can generate the counts we need for computing PCFG rule probabilities by first parsing a corpus of sentences with the parser. If sentences were unambiguous, it would be as simple as this: parse the corpus, increment a counter for every rule in the parse, and then normalize to get probabilities.

But wait! Since most sentences are ambiguous, that is, have multiple parses, we don't know which parse to count the rules in. Instead, we need to keep a separate count for each parse of a sentence and weight each of these partial counts by the probability of the parse it appears in. But to get these parse probabilities to weight the rules, we need to already have a probabilistic parser.

The intuition for solving this chicken-and-egg problem is to incrementally improve our estimates by beginning with a parser with equal rule probabilities, then parse the sentence, compute a probability for each parse, use these probabilities to weight the counts, re-estimate the rule probabilities, and so on, until our probabilities converge. The standard algorithm for computing this solution is called the **inside-outside** algorithm; it was proposed by Baker (1979) as a generalization of the forward-backward algorithm of Chapter 6. Like forward-backward, inside-outside is a special case of the Expectation Maximization (EM) algorithm, and hence has two steps: the **expectation step**, and the **maximization step**. See Lari and Young (1990) or Manning and Schütze (1999) for a complete description of the algorithm.

This use of the inside-outside algorithm to estimate the rule probabilities for a grammar is actually a kind of limited use of inside-outside. The inside-outside algorithm can actually be used not only to set the rule probabilities but even to induce the grammar rules themselves. It turns out, however, that grammar induction is so difficult that inside-outside by itself is not a very successful grammar inducer; see the Historical Notes at the end of the chapter for pointers to other grammar induction algorithms.

Inside-outside

Expectation step

Maximization step

14.4 Problems with PCFGs

While probabilistic context-free grammars are a natural extension to context-free grammars, they have two main problems as probability estimators:

Poor independence assumptions: CFG rules impose an independence assumption on probabilities, resulting in poor modeling of structural dependencies across the parse tree.

Lack of lexical conditioning: CFG rules don't model syntactic facts about specific words, leading to problems with subcategorization ambiguities, preposition attachment, and coordinate structure ambiguities.

Because of these problems, most current probabilistic parsing models use some augmented version of PCFGs, or modify the Treebank-based grammar in some way. In the next few sections after discussing the problems in more detail we introduce some of these augmentations.

14.4.1 Independence Assumptions Miss Structural Dependencies Between Rules

Let's look at these problems in more detail. Recall that in a CFG the expansion of a non-terminal is independent of the context, that is, of the other nearby non-terminals in the parse tree. Similarly, in a PCFG, the probability of a particular rule like $NP \rightarrow Det N$ is also independent of the rest of the tree. By definition, the probability of a group of independent events is the product of their probabilities. These two facts explain why in a PCFG we compute the probability of a tree by just multiplying the probabilities of each non-terminal expansion.

Unfortunately, this CFG independence assumption results in poor probability estimates. This is because in English the choice of how a node expands can after all depend on the location of the node in the parse tree. For example, in English it turns out that *NPs* that are syntactic **subjects** are far more likely to be pronouns, and *NPs* that are syntactic **objects** are far more likely to be non-pronominal (e.g., a proper noun or a determiner noun sequence), as shown by these statistics for *NPs* in the Switchboard corpus (Francis et al., 1999):¹

	Pronoun	Non-Pronoun
Subject	91%	9%
Object	34%	66%

Unfortunately, there is no way to represent this contextual difference in the probabilities in a PCFG. Consider two expansions of the non-terminal *NP* as a pronoun or as a determiner+noun. How shall we set the probabilities of these two rules? If we set

¹ Distribution of subjects from 31,021 declarative sentences; distribution of objects from 7,489 sentences. This tendency is caused by the use of subject position to realize the **topic** or old information in a sentence (Givón, 1990). Pronouns are a way to talk about old information, while non-pronominal ("lexical") noun-phrases are often used to introduce new referents. We talk more about new and old information in Chapter 21.

their probabilities to their overall probability in the Switchboard corpus, the two rules have about equal probability.

$$NP \rightarrow DT\ NN\ .28$$

$$NP \rightarrow PRP\ .25$$

Because PCFGs don't allow a rule probability to be conditioned on surrounding context, this equal probability is all we get; there is no way to capture the fact that in subject position, the probability for $NP \rightarrow PRP$ should go up to .91, while in object position, the probability for $NP \rightarrow DT\ NN$ should go up to .66.

These dependencies could be captured if the probability of expanding an NP as a pronoun (e.g., $NP \rightarrow PRP$) versus a lexical NP (e.g., $NP \rightarrow DT\ NN$) were *conditioned* on whether the NP was a subject or an object. Section 14.5 introduces the technique of **parent annotation** for adding this kind of conditioning.

14.4.2 Lack of Sensitivity to Lexical Dependencies

A second class of problems with PCFGs is their lack of sensitivity to the words in the parse tree. Words do play a role in PCFGs since the parse probability includes the probability of a word given a part-of-speech (i.e., from rules like $V \rightarrow sleep$, $NN \rightarrow book$, etc.).

But it turns out that lexical information is useful in other places in the grammar, such as in resolving prepositional phrase (PP) attachment ambiguities. Since prepositional phrases in English can modify a noun phrase or a verb phrase, when a parser finds a prepositional phrase, it must decide where to attach it into the tree. Consider the following example:

(14.19) Workers dumped sacks into a bin.

Figure 14.5 shows two possible parse trees for this sentence; the one on the left is the correct parse; Fig. 14.6 shows another perspective on the preposition attachment problem, demonstrating that resolving the ambiguity in Fig. 14.5 is equivalent to deciding whether to attach the prepositional phrase into the rest of the tree at the NP or VP nodes; we say that the correct parse requires **VP attachment**, and the incorrect parse implies **NP attachment**.

VP attachment
NP attachment

Why doesn't a PCFG already deal with PP attachment ambiguities? Note that the two parse trees in Fig. 14.5 have almost exactly the same rules; they differ only in that the left-hand parse has this rule:

$$VP \rightarrow VBD\ NP\ PP$$

while the right-hand parse has these:

$$VP \rightarrow VBD\ NP$$

$$NP \rightarrow NP\ PP$$

Depending on how these probabilities are set, a PCFG will **always** either prefer NP attachment or VP attachment. As it happens, NP attachment is slightly more common in English, so if we trained these rule probabilities on a corpus, we might always prefer NP attachment, causing us to misparse this sentence.

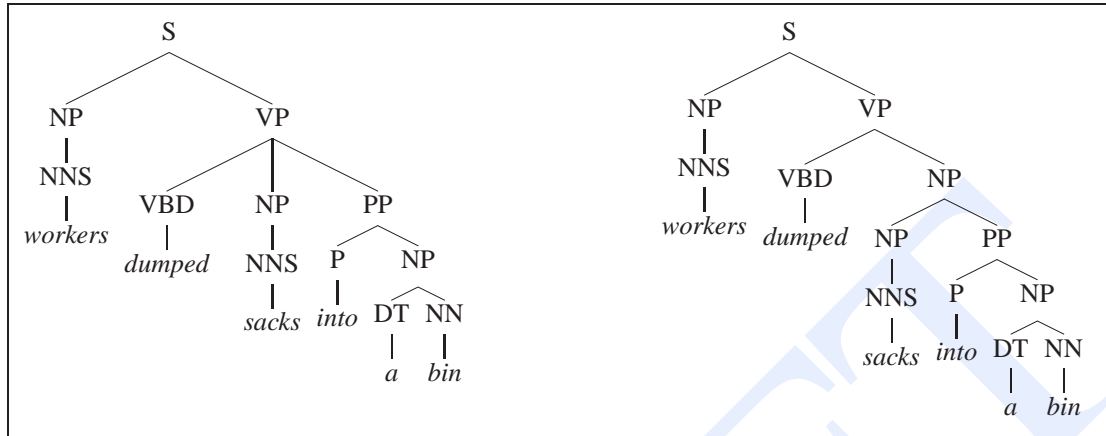


Figure 14.5 Two possible parse trees for a **prepositional phrase attachment ambiguity**. The left parse is the sensible one, in which “into a bin” describes the resulting location of the sacks. In the right incorrect parse, the sacks to be dumped are the ones which are already “into a bin”, whatever that might mean.

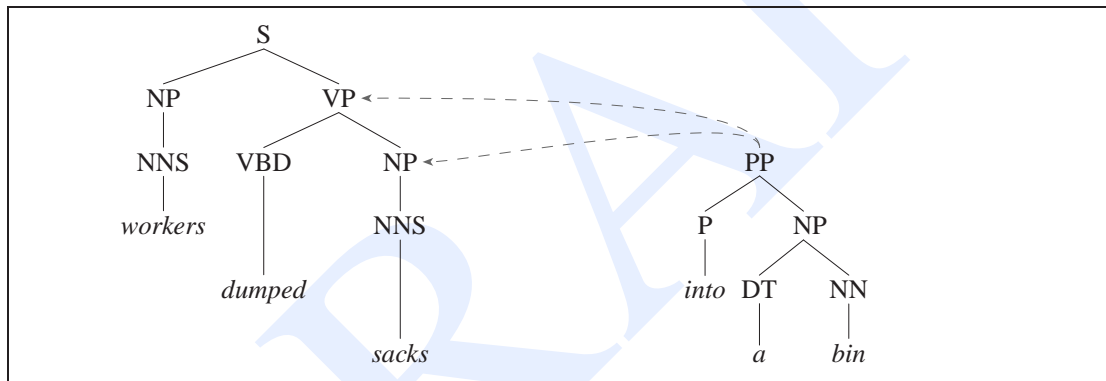


Figure 14.6 Another view of the preposition attachment problem. Should the *PP* on the right attach to the *VP* or *NP* nodes of the partial parse tree on the left?

But suppose we set the probabilities to prefer the *VP* attachment for this sentence. Now we would misparse the following sentence, which requires *NP* attachment:

(14.20) fishermen caught tons of herring

What information in the input sentence lets us know that (14.20) requires *NP* attachment while (14.19) requires *VP* attachment?

It should be clear that these preferences come from the identities of the verbs, nouns, and prepositions. It seems that the affinity between the verb *dumped* and the preposition *into* is greater than the affinity between the noun *sacks* and the preposition *into*, thus leading to *VP* attachment. On the other hand, in (14.20) the affinity between *tons* and *of* is greater than that between *caught* and *of*, leading to *NP* attachment.

Thus, to get the correct parse for these kinds of examples, we need a model that somehow augments the PCFG probabilities to deal with these **lexical dependency**

statistics for different verbs and prepositions.

Coordination ambiguities are another case in which lexical dependencies are the key to choosing the proper parse. Figure 14.7 shows an example from Collins (1999) with two parses for the phrase *dogs in houses and cats*. Because *dogs* is semantically a better conjunct for *cats* than *houses* (and because most dogs can't fit inside cats), the parse [*dogs in* [*NP houses and cats*]] is intuitively unnatural and should be dispreferred. The two parses in Fig. 14.7, however, have exactly the same PCFG rules, and thus a PCFG will assign them the same probability.

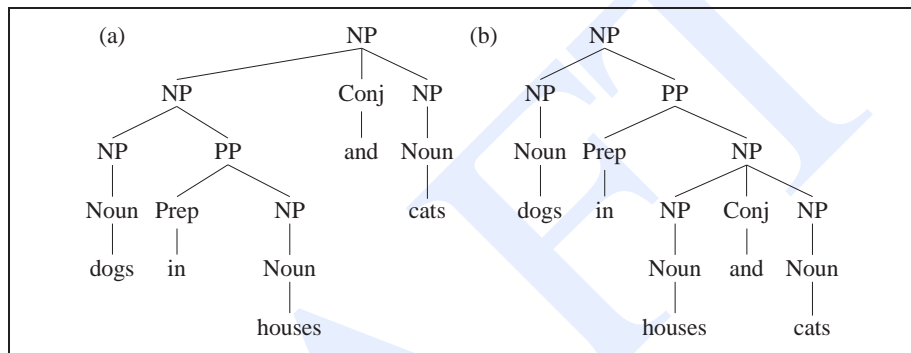


Figure 14.7 An instance of coordination ambiguity. Although the left structure is intuitively the correct one, a PCFG will assign them identical probabilities since both structures use exactly the same rules. After Collins (1999).

In summary, we have shown in this section and the previous one that probabilistic context-free grammars are incapable of modeling important **structural** and **lexical** dependencies. In the next two sections we sketch current methods for augmenting PCFGs to deal with both these issues.

14.5 Improving PCFGs by Splitting Non-Terminals

Let's start with the first of the two problems with PCFGs mentioned above: their inability to model structural dependencies, like the fact that NPs in subject position tend to be pronouns, whereas NPs in object position tend to have full lexical (non-pronominal) form. How could we augment a PCFG to correctly model this fact? One idea would be to **split** the *NP* non-terminal into two versions: one for subjects, one for objects. Having two nodes (e.g., $NP_{subject}$ and NP_{object}) would allow us to correctly model their different distributional properties, since we would have different probabilities for the rule $NP_{subject} \rightarrow PRP$ and the rule $NP_{object} \rightarrow PRP$.

One way to implement this intuition of splits is to do **parent annotation** (Johnson, 1998), in which we annotate each node with its parent in the parse tree. Thus, an *NP* node that is the subject of the sentence and hence has parent *S* would be annotated NP^S , while a direct object *NP* whose parent is *VP* would be annotated NP^{VP} . Figure 14.8 shows an example of a tree produced by a grammar that parent-annotates the phrasal

Split

Parent annotation

non-terminals (like *NP* and *VP*).

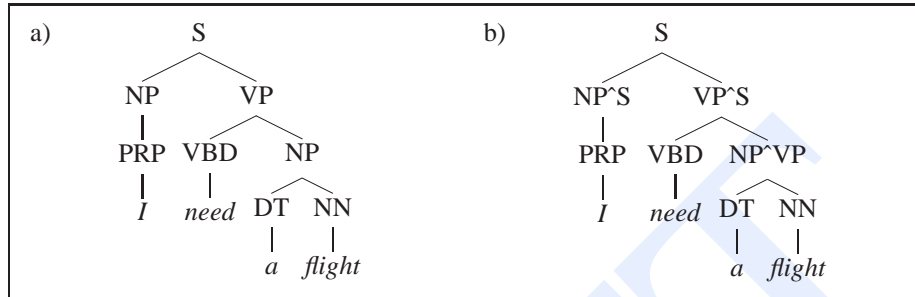


Figure 14.8 A standard PCFG parse tree (a) and one which has **parent annotation** on the nodes which aren't pre-terminal (b). All the non-terminal nodes (except the pre-terminal part-of-speech nodes) in parse (b) have been annotated with the identity of their parent.

In addition to splitting these phrasal nodes, we can also improve a PCFG by splitting the pre-terminal part-of-speech nodes (Klein and Manning, 2003b). For example, different kinds of adverbs (RB) tend to occur in different syntactic positions: the most common adverbs with ADVP parents are *also* and *now*, with *VP* parents *n't* and *not*, and with *NP* parents *only* and *just*. Thus, adding tags like *RB^ADVP*, *RB^VP*, and *RB^NP* can be useful in improving PCFG modeling.

Similarly, the Penn Treebank tag *IN* can mark a wide variety of parts-of-speech, including subordinating conjunctions (*while*, *as*, *if*), complementizers (*that*, *for*), and prepositions (*of*, *in*, *from*). Some of these differences can be captured by parent annotation (subordinating conjunctions occur under *S*, prepositions under *PP*), while others require specifically splitting the pre-terminal nodes. Figure 14.9 shows an example from Klein and Manning (2003b) in which even a parent-annotated grammar incor-

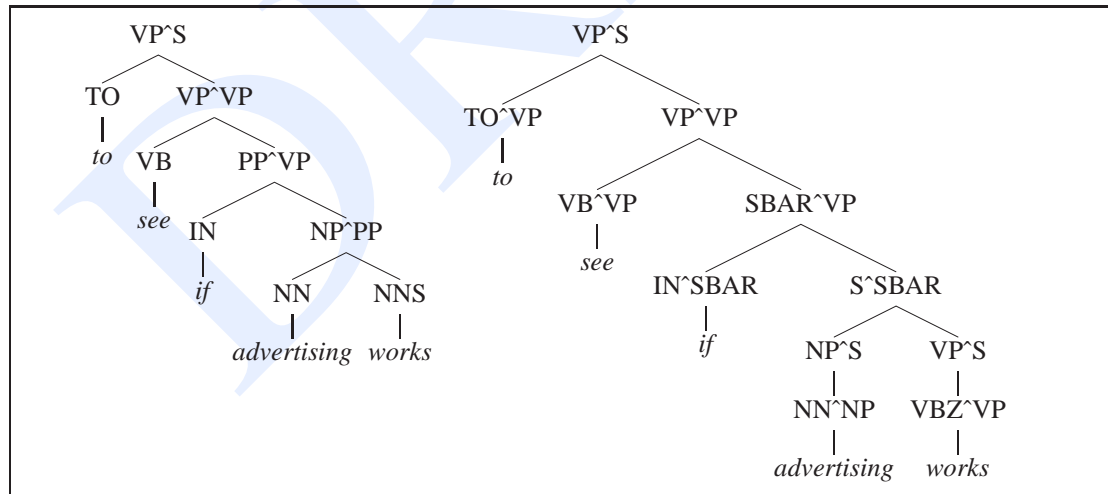


Figure 14.9 An incorrect parse even with a parent-annotated parse (left). The correct parse (right), was produced by a grammar in which the pre-terminal nodes have been split, allowing the probabilistic grammar to capture the fact that *if* prefers sentential complements. Adapted from Klein and Manning (2003b).

rectly parses *works* as a noun in *to see if advertising works*. Splitting pre-terminals to allow *if* to prefer a sentential complement results in the correct verbal parse.

DRAFT

To deal with cases in which parent annotation is insufficient, we can also hand-write rules that specify a particular node split based on other features of the tree. For example, to distinguish between complementizer IN and subordinating conjunction IN, both of which can have the same parent, we could write rules conditioned on other aspects of the tree such as the lexical identity (the lexeme *that* is likely to be a complementizer, *as* a subordinating conjunction).

Split and merge

Node-splitting is not without problems; it increases the size of the grammar and hence reduces the amount of training data available for each grammar rule, leading to overfitting. Thus, it is important to split to just the correct level of granularity for a particular training set. While early models employed hand-written rules to try to find an optimal number of non-terminals (Klein and Manning, 2003b), modern models automatically search for the optimal splits. The **split and merge** algorithm of Petrov et al. (2006), for example, starts with a simple X-bar grammar, alternately splits the non-terminals, and merges non-terminals, finding the set of annotated nodes that maximizes the likelihood of the training set treebank. As of the time of this writing, the performance of the Petrov et al. (2006) algorithm was the best of any known parsing algorithm on the Penn Treebank.

14.6 Probabilistic Lexicalized CFGs

The previous section showed that a simple probabilistic CKY algorithm for parsing raw PCFGs can achieve extremely high parsing accuracy if the grammar rule symbols are redesigned by automatic splits and merges.

Collins parser

Charniak parser

In this section, we discuss an alternative family of models in which instead of modifying the grammar rules, we modify the probabilistic model of the parser to allow for **lexicalized** rules. The resulting family of lexicalized parsers includes the well-known **Collins parser** (Collins, 1999) and **Charniak parser** (Charniak, 1997), both of which are publicly available and widely used throughout natural language processing.

Lexicalized grammar

We saw in Section ?? that syntactic constituents could be associated with a lexical **head**, and we defined a **lexicalized grammar** in which each non-terminal in the tree is annotated with its lexical head, where a rule like $VP \rightarrow VBD NP PP$ would be extended as

$$VP(dumped) \rightarrow VBD(dumped) NP(sacks) PP(into) \quad (14.21)$$

Head tag

In the standard type of lexicalized grammar, we actually make a further extension, which is to associate the **head tag**, the part-of-speech tags of the headwords, with the non-terminal symbols as well. Each rule is thus lexicalized by both the headword and the head tag of each constituent resulting in a format for lexicalized rules like

$$VP(dumped, VBD) \rightarrow VBD(dumped, VBD) NP(sacks, NNS) PP(into, IN) \quad (14.22)$$

We show a lexicalized parse tree with head tags in Fig. 14.10, extended from Fig. ??.

To generate such a lexicalized tree, each PCFG rule must be augmented to identify one right-hand constituent to be the head daughter. The headword for a node is then

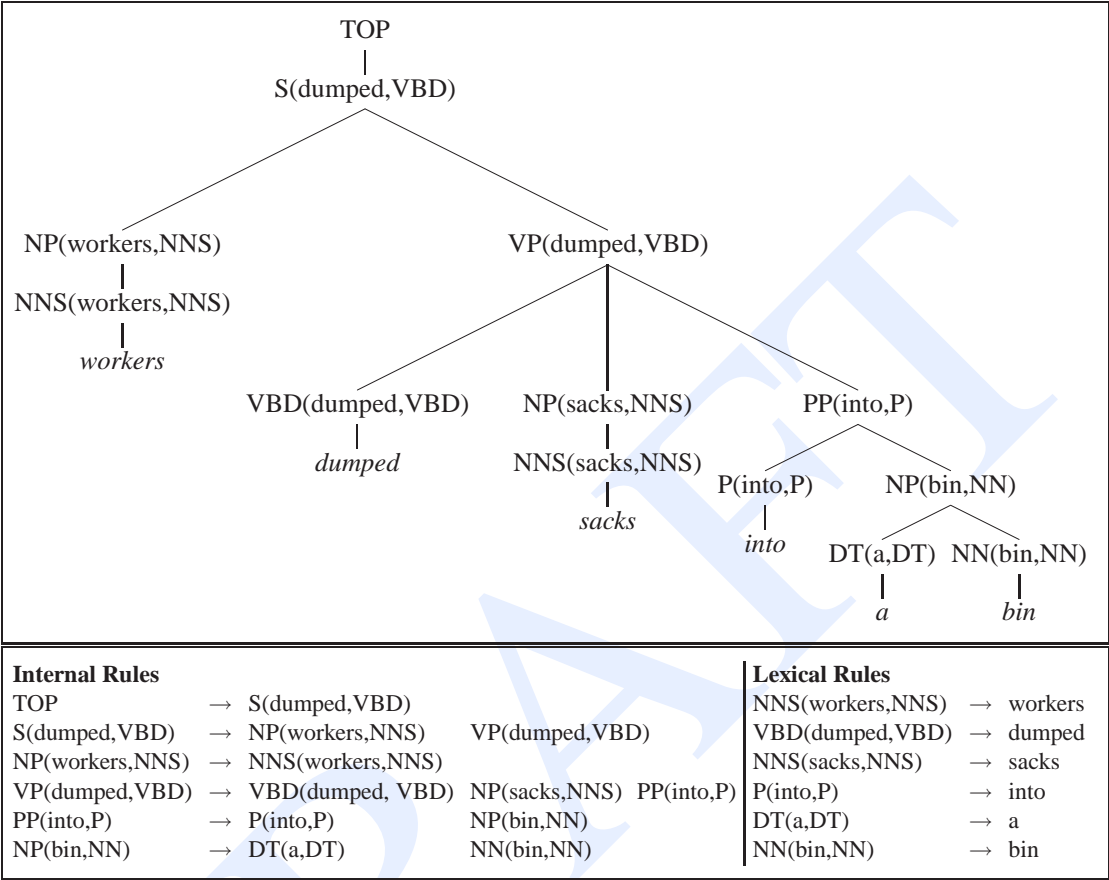


Figure 14.10 A lexicalized tree, including head tags, for a WSJ sentence, adapted from Collins (1999). Below we show the PCFG rules that would be needed for this parse tree, internal rules on the left, and lexical rules on the right.

set to the headword of its head daughter, and the head tag to the part-of-speech tag of the headword. Recall that we gave in Fig. ?? a set of hand-written rules for identifying the heads of particular constituents.

A natural way to think of a lexicalized grammar is as a parent annotation, that is, as a simple context-free grammar with many copies of each rule, one copy for each possible headword/head tag for each constituent. Thinking of a probabilistic lexicalized CFG in this way would lead to the set of simple PCFG rules shown below the tree in Fig. 14.10.

Note that Fig. 14.10 shows two kinds of rules: **lexical rules**, which express the expansion of a pre-terminal to a word, and **internal rules**, which express the other rule expansions. We need to distinguish these kinds of rules in a lexicalized grammar because they are associated with very different kinds of probabilities. The lexical rules are deterministic, that is, they have probability 1.0 since a lexicalized pre-terminal like $NN(bin, NN)$ can only expand to the word *bin*. But for the internal rules, we need to

estimate probabilities.

Suppose we were to treat a probabilistic lexicalized CFG like a really big CFG that just happened to have lots of very complex non-terminals and estimate the probabilities for each rule from maximum likelihood estimates. Thus, according to Eq. 14.18, the MLE estimate for the probability for the rule $P(VP(dumped, VBD) \rightarrow VBD(dumped, VBD) NP(sacks, NNS) PP(into, P))$ would be

$$\frac{\text{Count}(VP(dumped, VBD) \rightarrow VBD(dumped, VBD) NP(sacks, NNS) PP(into, P))}{\text{Count}(VP(dumped, VBD))} \quad (14.23)$$

But there's no way we can get good estimates of counts like those in (14.23) because they are so specific: we're unlikely to see many (or even any) instances of a sentence with a verb phrase headed by *dumped* that has one *NP* argument headed by *sacks* and a *PP* argument headed by *into*. In other words, counts of fully lexicalized PCFG rules like this will be far too sparse, and most rule probabilities will come out 0.

The idea of lexicalized parsing is to make some further independence assumptions to break down each rule so that we would estimate the probability

$$P(VP(dumped, VBD) \rightarrow VBD(dumped, VBD) NP(sacks, NNS) PP(into, P)) \quad (14.24)$$

as the product of smaller independent probability estimates for which we could acquire reasonable counts. The next section summarizes one such method, the Collins parsing method.

14.6.1 The Collins Parser

Modern statistical parsers differ in exactly which independence assumptions they make. In this section we describe a simplified version of Collins's (1999) Model 1, but a number of other parsers are worth knowing about; see the summary at the end of the chapter.

The first intuition of the Collins parser is to think of the right-hand side of every (internal) CFG rule as consisting of a head non-terminal, together with the non-terminals to the left of the head and the non-terminals to the right of the head. In the abstract, we think about these rules as follows:

$$LHS \rightarrow L_n L_{n-1} \dots L_1 H R_1 \dots R_{n-1} R_n \quad (14.25)$$

Since this is a lexicalized grammar, each of the symbols like L_1 or R_3 or H or LHS is actually a complex symbol representing the category and its head and head tag, like $VP(dumped, VP)$ or $NP(sacks, NNS)$.

Now, instead of computing a single MLE probability for this rule, we are going to break down this rule via a neat generative story, a slight simplification of what is called Collins Model 1. This new generative story is that given the left-hand side, we first generate the head of the rule and then generate the dependents of the head, one by one, from the inside out. Each of these generation steps will have its own probability.

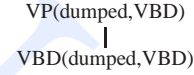
We also add a special STOP non-terminal at the left and right edges of the rule; this non-terminal allows the model to know when to stop generating dependents on a given

side. We generate dependents on the left side of the head until we've generated STOP on the left side of the head, at which point we move to the right side of the head and start generating dependents there until we generate STOP. So it's as if we are generating a rule augmented as follows:

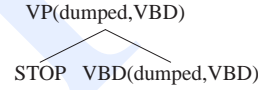
$$P(VP(dumped, VBD) \rightarrow \text{STOP } VBD(dumped, VBD) NP(sacks, NNS) PP(into, P) \text{ STOP}) \quad (14.26)$$

Let's see the generative story for this augmented rule. We make use of three kinds of probabilities: P_H for generating heads, P_L for generating dependents on the left, and P_R for generating dependents on the right.

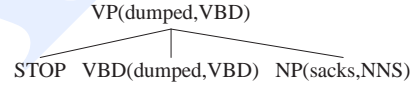
1) Generate the head VBD(dumped, VBD) with probability $P(H|LHS) = P(VBD(dumped, VBD) | VP(dumped, VBD))$



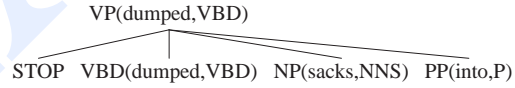
2) Generate the left dependent (which is STOP, since there isn't one) with probability $P(\text{STOP} | VP(dumped, VBD) \text{ VBD(dumped, VBD)})$



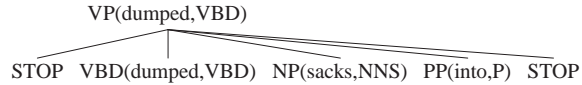
3) Generate right dependent NP(sacks, NNS) with probability $P_r(NP(sacks, NNS) | VP(dumped, VBD), VBD(dumped, VBD))$



4) Generate the right dependent PP(into, P) with probability $P_r(PP(into, P) | VP(dumped, VBD), VBD(dumped, VBD))$



5) Generate the right dependent STOP with probability $P_r(\text{STOP} | VP(dumped, VBD), VBD(dumped, VBD))$



In summary, the probability of this rule

$$P(VP(dumped, VBD) \rightarrow VBD(dumped, VBD) NP(sacks, NNS) PP(into, P)) \quad (14.27)$$

is estimated as

$$\begin{aligned} P_H(VBD | VP, dumped) &\times P_L(\text{STOP} | VP, VBD, dumped) \\ &\times P_R(NP(sacks, NNS) | VP, VBD, dumped) \\ &\times P_R(PP(into, P) | VP, VBD, dumped) \\ &\times P_R(\text{STOP} | VP, VBD, dumped) \end{aligned} \quad (14.28)$$

Each of these probabilities can be estimated from much smaller amounts of data than the full probability in (14.27). For example, the maximum likelihood estimate for the component probability $P_R(NP(sacks, NNS) | VP, VBD, dumped)$ is

$$\frac{\text{Count}(VP(dumped, VBD) \text{ with } NNS(sacks) \text{ as a daughter somewhere on the right})}{\text{Count}(VP(dumped, VBD))} \quad (14.29)$$

These counts are much less subject to sparsity problems than are complex counts like those in (14.27).

More generally, if we use h to mean a headword together with its tag, l to mean a word+tag on the left, and r to mean a word+tag on the right, then the probability of an entire rule can be expressed as follows:

1. Generate the head of the phrase $H(hw, ht)$ with probability:

$$P_H(H(hw, ht) | P, hw, ht)$$

2. Generate modifiers to the left of the head with total probability

$$\prod_{i=1}^{n+1} P_L(L_i(lw_i, lt_i) | P, H, hw, ht)$$

such that $L_{n+1}(lw_{n+1}, lt_{n+1}) = \text{STOP}$, and we stop generating once we've generated a STOP token.

3. Generate modifiers to the right of the head with total probability:

$$\prod_{i=1}^{n+1} P_R(R_i(rw_i, rt_i) | P, H, hw, ht)$$

such that $R_{n+1}(rw_{n+1}, rt_{n+1}) = \text{STOP}$, and we stop generating once we've generated a STOP token.

14.6.2 Advanced: Further Details of the Collins Parser

Distance

The actual Collins parser models are more complex (in a couple of ways) than the simple model presented in the previous section. Collins Model 1 includes a **distance** feature. Thus, instead of computing P_L and P_R as follows,

$$P_L(L_i(lw_i, lt_i) | P, H, hw, ht) \quad (14.30)$$

$$P_R(R_i(rw_i, rt_i) | P, H, hw, ht) \quad (14.31)$$

Collins Model 1 conditions also on a distance feature:

$$P_L(L_i(lw_i, lt_i) | P, H, hw, ht, \text{distance}_L(i-1)) \quad (14.32)$$

$$P_R(R_i(rw_i, rt_i) | P, H, hw, ht, \text{distance}_R(i-1)) \quad (14.33)$$

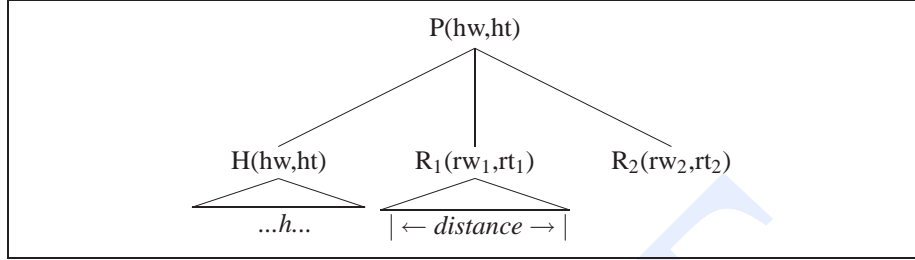


Figure 14.11 R_2 is generated with probability $P(R_2(rh_2, rt_2) | P, H, hw, ht, distance_R(1))$. The distance is the yield of the previous dependent non-terminal R_1 . Had there been another intervening dependent, its yield would have been included as well. Adapted from Collins (2003).

The distance measure is a function of the sequence of words *below* the previous modifiers (i.e., the words that are the yield of each modifier non-terminal we have already generated on the left). Figure 14.11, adapted from Collins (2003), shows the computation of the probability $P(R_2(rh_2, rt_2) | P, H, hw, ht, distance_R(1))$.

The simplest version of this distance measure is just a tuple of two binary features based on the surface string below these previous dependencies: (1) Is the string of length zero? (i.e., were no previous words generated?) (2) Does the string contain a verb?

Collins Model 2 adds more sophisticated features, conditioning on subcategorization frames for each verb and distinguishing arguments from adjuncts.

Finally, smoothing is as important for statistical parsers as it was for N -gram models. This is particularly true for lexicalized parsers, since the lexicalized rules will otherwise condition on many lexical items that may never occur in training (even using the Collins or other methods of independence assumptions).

Consider the probability $P_R(R_i(rw_i, rt_i) | P, hw, ht)$. What do we do if a particular right-hand constituent never occurs with this head? The Collins model addresses this problem by interpolating three backed-off models: fully lexicalized (conditioning on the headword), backing off to just the head tag, and altogether unlexicalized.

Backoff Level	$P_R(R_i(rw_i, rt_i) | \dots)$	Example
1	$P_R(R_i(rw_i, rt_i) | P, hw, ht)$	$P_R(NP(sacks, NNS) | VP, VBD, dumped)$
2	$P_R(R_i(rw_i, rt_i) | P, ht)$	$P_R(NP(sacks, NNS) | VP, VBD)$
3	$P_R(R_i(rw_i, rt_i) | P)$	$P_R(NP(sacks, NNS) | VP)$

Similar backoff models are built also for P_L and P_H . Although we've used the word "backoff", in fact these are not backoff models but interpolated models. The three models above are linearly interpolated, where e_1 , e_2 , and e_3 are the maximum likelihood estimates of the three backoff models above:

$$P_R(\dots) = \lambda_1 e_1 + (1 - \lambda_1)(\lambda_2 e_2 + (1 - \lambda_2) e_3) \quad (14.34)$$

The values of λ_1 and λ_2 are set to implement Witten-Bell discounting (Witten and Bell, 1991) following Bikel et al. (1997).

The Collins model deals with unknown words by replacing any unknown word in the test set, and any word occurring less than six times in the training set, with a special

UNKNOWN word token. Unknown words in the test set are assigned a part-of-speech tag in a preprocessing step by the Ratnaparkhi (1996) tagger; all other words are tagged as part of the parsing process.

The parsing algorithm for the Collins model is an extension of probabilistic CKY; see Collins (2003). Extending the CKY algorithm to handle basic lexicalized probabilities is left as Exercises 14.5 and 14.6 for the reader.

14.7 Evaluating Parsers

The standard techniques for evaluating parsers and grammars are called the PARSEVAL measures; they were proposed by Black et al. (1991) and were based on the same ideas from signal-detection theory that we saw in earlier chapters. The intuition of the PARSEVAL metric is to measure how much the **constituents** in the hypothesis parse tree look like the constituents in a hand-labeled, gold-reference parse. PARSEVAL thus assumes we have a human-labeled “gold standard” parse tree for each sentence in the test set; we generally draw these gold-standard parses from a treebank like the Penn Treebank.

Given these gold-standard reference parses for a test set, a given constituent in a hypothesis parse C_h of a sentence s is labeled “correct” if there is a constituent in the reference parse C_r with the same starting point, ending point, and non-terminal symbol.

We can then measure the precision and recall just as we did for chunking in the previous chapter.

$$\text{labeled recall} = \frac{\# \text{ of correct constituents in hypothesis parse of } s}{\# \text{ of correct constituents in reference parse of } s}$$

$$\text{labeled precision} = \frac{\# \text{ of correct constituents in hypothesis parse of } s}{\# \text{ of total constituents in hypothesis parse of } s}$$

F-measure

As with other uses of precision and recall, instead of reporting them separately, we often report a single number, the **F-measure** (van Rijsbergen, 1975): The *F-measure* is defined as

$$F_\beta = \frac{(\beta^2 + 1)PR}{\beta^2 P + R}$$

The β parameter differentially weights the importance of recall and precision, based perhaps on the needs of an application. Values of $\beta > 1$ favor recall and values of $\beta < 1$ favor precision. When $\beta = 1$, precision and recall are equally balanced; this is sometimes called $F_{\beta=1}$ or just F_1 :

$$F_1 = \frac{2PR}{P + R} \quad (14.35)$$

The *F-measure* derives from a weighted harmonic mean of precision and recall. Remember that the harmonic mean of a set of numbers is the reciprocal of the arithmetic

mean of the reciprocals:

$$\text{HarmonicMean}(a_1, a_2, a_3, a_4, \dots, a_n) = \frac{n}{\frac{1}{a_1} + \frac{1}{a_2} + \frac{1}{a_3} + \dots + \frac{1}{a_n}} \quad (14.36)$$

and hence the F -measure is

$$F = \frac{1}{\alpha \frac{1}{P} + (1 - \alpha) \frac{1}{R}} \quad \text{or} \quad \left(\text{with } \beta^2 = \frac{1 - \alpha}{\alpha} \right) \quad F = \frac{(\beta^2 + 1)PR}{\beta^2 P + R} \quad (14.37)$$

We additionally use a new metric, crossing brackets, for each sentence s :

cross-brackets: the number of constituents for which the reference parse has a bracketing such as ((A B) C) but the hypothesis parse has a bracketing such as (A (B C)).

As of the time of this writing, the performance of modern parsers that are trained and tested on the *Wall Street Journal* treebank was somewhat higher than 90% recall, 90% precision, and about 1% cross-bracketed constituents per sentence.

For comparing parsers that use different grammars, the PARSEVAL metric includes a canonicalization algorithm for removing information likely to be grammar-specific (auxiliaries, pre-infinitival “to”, etc.) and for computing a simplified score. The interested reader should see Black et al. (1991). The canonical publicly available implementation of the PARSEVAL metrics is called **evalb** (Sekine and Collins, 1997).

evalb

You might wonder why we don’t evaluate parsers by measuring how many *sentences* are parsed correctly instead of measuring *constituent* accuracy. The reason we use constituents is that measuring constituents gives us a more fine-grained metric. This is especially true for long sentences, where most parsers don’t get a perfect parse. If we just measured sentence accuracy, we wouldn’t be able to distinguish between a parse that got most of the constituents wrong and one that just got one constituent wrong.

Nonetheless, constituents are not always an optimal unit for parser evaluation. For example, using the PARSEVAL metrics requires that our parser produce trees in the exact same format as the gold standard. That means that if we want to evaluate a parser which produces different styles of parses (dependency parses, or LFG feature-structures, etc.) against, say, the Penn Treebank (or against another parser that produces Treebank format), we need to map the output parses into Treebank format. A related problem is that constituency may not be the level we care the most about. We might be more interested in how well the parser does at recovering grammatical dependencies (subject, object, etc.), which could give us a better metric for how useful the parses would be to semantic understanding. For these purposes, we can use alternative evaluation metrics based on measuring the precision and recall of labeled dependencies, where the labels indicate the grammatical relations (Lin, 1995; Carroll et al., 1998; Collins et al., 1999). Kaplan et al. (2004), for example, compared the Collins (1999) parser with the Xerox XLE parser (Riezler et al., 2002), which produces much richer semantic representations by converting both parse trees to a dependency representation.

14.8 Advanced: Discriminative Reranking

The models we have seen of parsing so far, the PCFG parser and the Collins lexicalized parser, are generative parsers. By this we mean that the probabilistic model implemented in these parsers gives us the probability of generating a particular sentence by assigning a probability to each choice the parser could make in this generation procedure.

Generative models have some significant advantages; they are easy to train with maximum likelihood, and they give us an explicit model of how different sources of evidence are combined. But generative parsing models also make it hard to incorporate arbitrary kinds of information into the probability model. This is because the probability is based on the generative derivation of a sentence; it is difficult to add features that are not local to a particular PCFG rule.

Consider, for example, how to represent global facts about tree structure. Parse trees in English tend to be right-branching; we'd therefore like our model to assign a higher probability to a tree that is more right-branching, all else being equal. It is also the case that heavy constituents (those with a large number of words) tend to appear later in the sentence. Or we might want to condition our parse probabilities on global facts like the identity of the speaker (perhaps some speakers are more likely to use complex relative clauses or to use the passive). Or we might want to condition on complex discourse factors across sentences. None of these kinds of global factors are trivial to incorporate into the generative models we have been considering. A simplistic model that, for example, makes each non-terminal dependent on how right-branching the tree is in the parse so far, or makes each *NP* non-terminal sensitive to the number of relative clauses the speaker or writer used in previous sentences, would result in counts that are far too sparse.

We discussed this problem in Chapter 6, where the need for these kinds of global features motivated the use of log-linear (MEMM) models for POS tagging instead of HMMs. For parsing, there are two broad classes of discriminative models: dynamic programming approaches and two-stage models of parsing that use discriminative reranking. We discuss discriminative reranking in the rest of this section; see the end of the chapter for pointers to discriminative dynamic programming approaches.

In the first stage of a discriminative reranking system, we can run a normal statistical parser of the type we've described so far. But instead of just producing the single best parse, we modify the parser to produce a ranked list of parses together with their probabilities. We call this ranked list of N parses the **N -best list** (the N -best list was first introduced in Chapter 9 in a discussion of multiple-pass decoding models for speech recognition). There are various ways to modify statistical parsers to produce an N -best list of parses; see the end of the chapter for pointers to the literature. For each sentence in the training set and the test set, we run this N -best parser and produce a set of N parse/probability pairs.

The second stage of a discriminative reranking model is a classifier that takes each of these sentences with their N parse/probability pairs as input, extracts some large set of features, and chooses the single best parse from the N -best list. We can rerank with any type of classifier, such as the log-linear classifiers introduced in Chapter 6.

N-best list

A wide variety of features can be used for reranking. One important feature to include is the parse probability assigned by the first-stage statistical parser. Other features might include each of the CFG rules in the tree, the number of parallel conjuncts, the heaviness of each constituent, measures of how right-branching the parse tree is, the number of times various tree fragments occur, bigrams of adjacent non-terminals in the tree, and so on.

Oracle accuracy

The two-stage architecture has a weakness: the accuracy rate of the complete architecture can never be better than the accuracy rate of the best parse in the first-stage N -best list. This is because reranking methods merely choose one of the N -best parses; even if we picked the very best parse in the list, we can't get 100% accuracy if the correct parse isn't in the list! Therefore, it is important to consider the ceiling **oracle accuracy** (often measured in F -measure) of the N -best list. The oracle accuracy of a particular N -best list is the accuracy we get if we chose the parse that had the highest accuracy. We call this an **oracle** accuracy because it relies on perfect knowledge (as if from an oracle) of which parse to pick.² Of course it only makes sense to implement discriminative reranking if the N -best F -measure is higher than the 1-best F -measure. Luckily, this is often the case; for example the Charniak (2000) parser has an F -measure of 0.897 on section 23 of the Penn Treebank, but the Charniak and Johnson (2005) algorithm for producing the 50-best parses has a much higher oracle F -measure of 0.968.

14.9 Advanced: Parser-Based Language Modeling

We said earlier that statistical parsers can take advantage of longer-distance information than N -grams, which suggests that they might do a better job at language modeling/word prediction. It turns out that if we have a very large amount of training data, a 4-gram or 5-gram grammar is nonetheless still the best way to do language modeling. But in situations in which there is not enough data for such huge models, parser-based language models that have higher accuracy than N -gram models are beginning to be developed.

Two common applications for language modeling are speech recognition and machine translation. The simplest way to use a statistical parser for language modeling for either of these applications is through a two-stage algorithm of the type discussed in the previous section and in Section ?? . In the first stage, we run a normal speech recognition decoder, or machine translation decoder, using a normal N -gram grammar. But instead of just producing the single best transcription or translation sentence, we modify the decoder to produce a ranked N -best list of transcriptions/translations sentences, each one together with its probability (or, alternatively, a lattice).

Then in the second stage, we run our statistical parser and assign a parse probability to each sentence in the N -best list or lattice. We then rerank the sentences based on this parse probability and choose the single best sentence. This algorithm can work better than using a simple trigram grammar. For example, on the task of recognizing

² We introduced this same oracle idea in Chapter 9 when we talked about the **lattice error rate**.

spoken sentences from the *Wall Street Journal* with this two-stage architecture, the probabilities assigned by the Charniak (2001) parser improved the word error rate by about 2% absolute, over a simple trigram grammar computed on 40 million words (Hall and Johnson, 2003). We can either use the parse probabilities assigned by the parser as-is or we can linearly combine it with the original N -gram probability.

An alternative to the two-pass architecture, at least for speech recognition, is to modify the parser to run strictly left to right, so that it can incrementally give the probability of the next word in the sentence. This would allow the parser to be fit directly into the first-pass decoding pass and would obviate the second pass altogether. While a number of such left-to-right, parser-based language modeling algorithms exist (Stolcke, 1995; Jurafsky et al., 1995; Roark, 2001; Xu et al., 2002), it is fair to say that it is still early days for the field of parser-based statistical language models.

14.10 Human Parsing

Human sentence processing

Are the kinds of probabilistic parsing models we have been discussing also used by humans when they are parsing? The answer to this question lies in a field called **human sentence processing**. Recent studies suggest that there are at least two ways in which humans apply probabilistic parsing algorithms, although there is still disagreement on the details.

Reading time

One family of studies has shown that when humans read, the predictability of a word seems to influence the **reading time**; more predictable words are read more quickly. One way of defining predictability is from simple bigram measures. For example, Scott and Shillcock (2003) used an eye-tracker to monitor the gaze of participants reading sentences. They constructed the sentences so that some would have a verb-noun pair with a high bigram probability (such as (14.38a)) and others a verb-noun pair with a low bigram probability (such as (14.38b)).

- (14.38) a) **HIGH PROB:** One way to **avoid confusion** is to make the changes during vacation
 b) **LOW PROB:** One way to **avoid discovery** is to make the changes during vacation

They found that the higher the bigram predictability of a word, the shorter the time that participants looked at the word (the **initial-fixation duration**).

While this result provides evidence only for N -gram probabilities, more recent experiments have suggested that the probability of an upcoming word given the syntactic parse of the preceding sentence prefix also predicts word reading time (Hale, 2001; Levy, 2008).

Interestingly, this effect of probability on reading time has also been shown for morphological structure; the time to recognize a word is influenced by entropy of the word and the entropy of the word's morphological paradigm (Moscato del Prado Martín et al., 2004).

The second family of studies has examined how humans disambiguate sentences that have multiple possible parses, suggesting that humans prefer whichever parse is

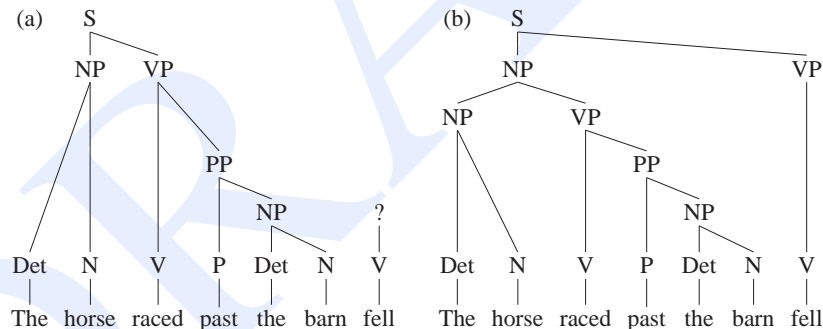
Garden-path

more probable. These studies often rely on a specific class of temporarily ambiguous sentences called **garden-path** sentences. These sentences, first described by Bever (1970), are sentences that are cleverly constructed to have three properties that combine to make them very difficult for people to parse:

1. They are **temporarily ambiguous**: The sentence is unambiguous, but its initial portion is ambiguous.
2. One of the two or more parses in the initial portion is somehow preferable to the human parsing mechanism.
3. But the dispreferred parse is the correct one for the sentence.

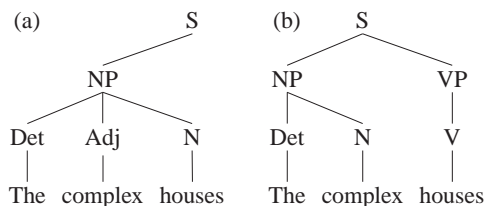
The result of these three properties is that people are “led down the garden path” toward the incorrect parse and then are confused when they realize it’s the wrong one. Sometimes this confusion is quite conscious, as in Bever’s example (14.39); in fact, this sentence is so hard to parse that readers often need to be shown the correct structure. In the correct structure, *raced* is part of a reduced relative clause modifying *The horse*, and means “The horse [which was raced past the barn] fell”; this structure is also present in the sentence “Students taught by the Berlitz method do worse when they get to France”.

(14.39) The horse raced past the barn fell.

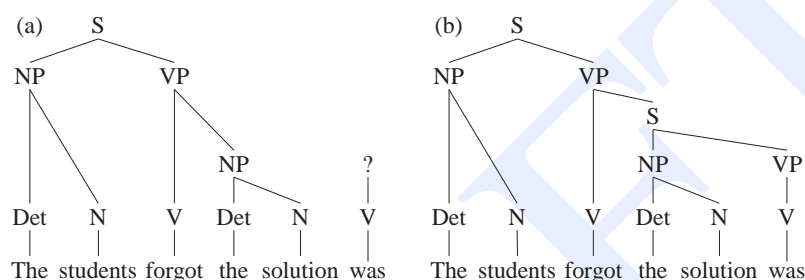


In Marti Hearst’s example (14.40), readers often misparse the verb *houses* as a noun (analyzing *the complex houses* as a noun phrase, rather than a noun phrase and a verb). Other times, the confusion caused by a garden-path sentence is so subtle that it can only be measured by a slight increase in reading time. Thus, in (14.41) readers often misparse *the solution* as the direct object of *forgot* rather than as the subject of an embedded sentence. This misparse is subtle, and is only noticeable because experimental participants take longer to read the word *was* than in control sentences. This “mini garden path” effect at the word *was* suggests that subjects had chosen the direct object parse and had to reanalyze or rearrange their parse now that they realize they are in a sentential complement.

(14.40) The complex houses married and single students and their families.



(14.41) The student forgot the solution was in the back of the book.



While many factors seem to play a role in these preferences for a particular (incorrect) parse, at least one factor seems to be syntactic probabilities, especially lexicalized (subcategorization) probabilities. For example, the probability of the verb *forgot* taking a direct object ($VP \rightarrow VNP$) is higher than the probability of it taking a sentential complement ($VP \rightarrow VS$); this difference causes readers to expect a direct object after *forget* and be surprised (longer reading times) when they encounter a sentential complement. By contrast, a verb which prefers a sentential complement (like *hope*) didn't cause extra reading time at *was*.

The garden path in (14.40) may arise from the fact that $P(\text{houses}|\text{Noun})$ is higher than $P(\text{houses}|\text{Verb})$ and $P(\text{complex}|\text{Adjective})$ is higher than $P(\text{complex}|\text{Noun})$, and the garden path in (14.39) at least partially caused by the low probability of the reduced relative clause construction.

Besides grammatical knowledge, human parsing is affected by many other factors which we describe later, including resource constraints (such as memory limitations, discussed in Chapter 16), thematic structure (such as whether a verb expects semantic *agents* or *patients*, discussed in Chapter 19) and discourse constraints (Chapter 21).

14.11 Summary

This chapter has sketched the basics of **probabilistic parsing**, concentrating on **probabilistic context-free grammars** and **probabilistic lexicalized context-free grammars**.

- Probabilistic grammars assign a probability to a sentence or string of words while attempting to capture more sophisticated syntactic information than the N -gram grammars of Chapter 4.

- A **probabilistic context-free grammar (PCFG)** is a context-free grammar in which every rule is annotated with the probability of that rule being chosen. Each PCFG rule is treated as if it were **conditionally independent**; thus, the probability of a sentence is computed by **multiplying** the probabilities of each rule in the parse of the sentence.
- The probabilistic CKY (**Cocke-Kasami-Younger**) algorithm is a probabilistic version of the CKY parsing algorithm. There are also probabilistic versions of other parsers like the Earley algorithm.
- PCFG probabilities can be learned by counting in a **parsed corpus** or by parsing a corpus. The **inside-outside** algorithm is a way of dealing with the fact that the sentences being parsed are ambiguous.
- Raw PCFGs suffer from poor independence assumptions among rules and lack of sensitivity to lexical dependencies.
- One way to deal with this problem is to split and merge non-terminals (automatically or by hand).
- **Probabilistic lexicalized CFGs** are another solution to this problem in which the basic PCFG model is augmented with a **lexical head** for each rule. The probability of a rule can then be conditioned on the lexical head or nearby heads.
- Parsers for lexicalized PCFGs (like the Charniak and Collins parsers) are based on extensions to probabilistic CKY parsing.
- Parsers are evaluated with three metrics: **labeled recall**, **labeled precision**, and **cross-brackets**.
- Evidence from **garden-path sentences** and other on-line sentence-processing experiments suggest that the human parser uses some kinds of probabilistic information about grammar.

Bibliographical and Historical Notes

Many of the formal properties of probabilistic context-free grammars were first worked out by Booth (1969) and Salomaa (1969). Baker (1979) proposed the inside-outside algorithm for unsupervised training of PCFG probabilities, and used a CKY-style parsing algorithm to compute inside probabilities. Jelinek and Lafferty (1991) extended the CKY algorithm to compute probabilities for prefixes. Stolcke (1995) drew on both of these algorithms in adapting the Earley algorithm to use with PCFGs.

A number of researchers starting in the early 1990s worked on adding lexical dependencies to PCFGs and on making PCFG rule probabilities more sensitive to surrounding syntactic structure. For example, Schabes et al. (1988) and Schabes (1990) presented early work on the use of heads. Many papers on the use of lexical dependencies were first presented at the DARPA Speech and Natural Language Workshop in June 1990. A paper by Hindle and Rooth (1990) applied lexical dependencies to the problem of attaching prepositional phrases; in the question session to a later paper, Ken Church suggested applying this method to full parsing (Marcus, 1990). Early work on

such probabilistic CFG parsing augmented with probabilistic dependency information includes Magerman and Marcus (1991), Black et al. (1992), Bod (1993), and Jelinek et al. (1994), in addition to Collins (1996), Charniak (1997), and Collins (1999) discussed above. Other recent PCFG parsing models include Klein and Manning (2003a) and Petrov et al. (2006).

This early lexical probabilistic work led initially to work focused on solving specific parsing problems like preposition-phrase attachment by using methods including transformation-based learning (TBL) (Brill and Resnik, 1994), maximum entropy (Ratnaparkhi et al., 1994), memory-based Learning (Zavrel and Daelemans, 1997), log-linear models (Franz, 1997), decision trees that used semantic distance between heads (computed from WordNet) (Stetina and Nagao, 1997), and boosting (Abney et al., 1999).

Another direction extended the lexical probabilistic parsing work to build probabilistic formulations of grammars other than PCFGs, such as probabilistic TAG grammar (Resnik, 1992; Schabes, 1992), based on the TAG grammars discussed in Chapter 12, probabilistic LR parsing (Briscoe and Carroll, 1993), and probabilistic link grammar (Lafferty et al., 1992). An approach to probabilistic parsing called **supertagging** extends the part-of-speech tagging metaphor to parsing by using very complex tags that are, in fact, fragments of lexicalized parse trees (Bangalore and Joshi, 1999; Joshi and Srinivas, 1994), based on the lexicalized TAG grammars of Schabes et al. (1988). For example, the noun *purchase* would have a different tag as the first noun in a noun compound (where it might be on the left of a small tree dominated by Nominal) than as the second noun (where it might be on the right). Supertagging has also been applied to CCG parsing and HPSG parsing (Clark and Curran, 2004a; Matsuzaki et al., 2007; Blunsom and Baldwin, 2006). Non-supertagging statistical parsers for CCG include Hockenmaier and Steedman (2002).

Goodman (1997), Abney (1997), and Johnson et al. (1999) gave early discussions of probabilistic treatments of feature-based grammars. Other recent work on building statistical models of feature-based grammar formalisms like HPSG and LFG includes Riezler et al. (2002), Kaplan et al. (2004), and Toutanova et al. (2005).

We mentioned earlier that discriminative approaches to parsing fall into the two broad categories of dynamic programming methods and discriminative reranking methods. Recall that discriminative reranking approaches require N -best parses. Parsers based on A^* search can easily be modified to generate N -best lists just by continuing the search past the first-best parse (Roark, 2001). Dynamic programming algorithms like the ones described in this chapter can be modified by the elimination of the dynamic programming with heavy pruning (Collins, 2000; Collins and Koo, 2005; Bikel, 2004), or through new algorithms (Jiménez and Marzal, 2000; Charniak and Johnson, 2005; Huang and Chiang, 2005), some adapted from speech recognition algorithms such as those of Schwartz and Chow (1990) (see Section ??).

In dynamic programming methods, instead of outputting and then reranking an N -best list, the parses are represented compactly in a chart, and log-linear and other methods are applied for decoding directly from the chart. Such modern methods include Johnson (2001), Clark and Curran (2004b), and Taskar et al. (2004). Other reranking developments include changing the optimization criterion (Titov and Henderson, 2006).

Non-projective dependencies

Another important recent area of research is dependency parsing; algorithms include Eisner's bilexical algorithm (Eisner, 1996b, 1996a, 2000), maximum spanning tree approaches (using on-line learning) (McDonald et al., 2005a, 2005b), and approaches based on building classifiers for parser actions (Kudo and Matsumoto, 2002; Yamada and Matsumoto, 2003; Nivre et al., 2006; Titov and Henderson, 2007). A distinction is usually made between projective and **non-projective dependencies**. Non-projective dependencies are those in which the dependency lines can cross; this is not common in English but is very common in many languages with more free word order. Non-projective dependency algorithms include McDonald et al. (2005b) and Nivre (2007). The Klein-Manning parser combines dependency and constituency information (Klein and Manning, 2003c).

Collins' (1999) dissertation includes a very readable survey of the field and an introduction to his parser. Manning and Schütze (1999) extensively cover probabilistic parsing.

The field of grammar induction is closely related to statistical parsing, and a parser is often used as part of a grammar induction algorithm. One of the earliest statistical works in grammar induction was Horning (1969), who showed that PCFGs could be induced without negative evidence. Early modern probabilistic grammar work showed that simply using EM was insufficient (Lari and Young, 1990; Carroll and Charniak, 1992). Recent probabilistic work, such as Yuret (1998), Clark (2001), Klein and Manning (2002), and Klein and Manning (2004), are summarized in Klein (2005) and Adriaans and van Zaanen (2004). Work since that summary includes Smith and Eisner (2005), Haghighi and Klein (2006), and Smith and Eisner (2007).

Exercises

- 14.1 Implement the CKY algorithm.
- 14.2 Modify the algorithm for conversion to CNF from Chapter 13 to correctly handle rule probabilities. Make sure that the resulting CNF assigns the same total probability to each parse tree.
- 14.3 Recall that Exercise 13.3 asked you to update the CKY algorithm to handle unit productions directly rather than converting them to CNF. Extend this change to probabilistic CKY.
- 14.4 Fill out the rest of the probabilistic CKY chart in Fig. 14.4.
- 14.5 Sketch how the CKY algorithm would have to be augmented to handle lexicalized probabilities.
- 14.6 Implement your lexicalized extension of the CKY algorithm.
- 14.7 Implement the PARSEVAL metrics described in Section 14.7. Next, either use a treebank or create your own hand-checked parsed testset. Now use your CFG (or other) parser and grammar, parse the test set and compute labeled recall, labeled precision, and cross-brackets.

- Abney, S. P. (1997). Stochastic attribute-value grammars. *Computational Linguistics*, 23(4), 597–618.
- Abney, S. P., Schapire, R. E., and Singer, Y. (1999). Boosting applied to tagging and PP attachment. In *EMNLP/VLC-99*, College Park, MD, pp. 38–45.
- Adriaans, P. and van Zaanen, M. (2004). Computational grammar induction for linguists. *Grammars; special issue with the theme “Grammar Induction”*, 7, 57–68.
- Baker, J. K. (1979). Trainable grammars for speech recognition. In Klatt, D. H. and Wolf, J. J. (Eds.), *Speech Communication Papers for the 97th Meeting of the Acoustical Society of America*, pp. 547–550.
- Bangalore, S. and Joshi, A. K. (1999). Supertagging: An approach to almost parsing. *Computational Linguistics*, 25(2), 237–265.
- Bever, T. G. (1970). The cognitive basis for linguistic structures. In Hayes, J. R. (Ed.), *Cognition and the Development of Language*, pp. 279–352. Wiley.
- Bikel, D. M. (2004). Intricacies of Collins’ parsing model. *Computational Linguistics*, 30(4), 479–511.
- Bikel, D. M., Miller, S., Schwartz, R., and Weischedel, R. (1997). Nymble: A high-performance learning name-finder. In *ANLP 1997*, pp. 194–201.
- Black, E., Abney, S. P., Flickinger, D., Gdaniec, C., Grishman, R., Harrison, P., Hindle, D., Ingria, R., Jelinek, F., Klavans, J. L., Liberman, M. Y., Marcus, M. P., Roukos, S., Santorini, B., and Strzalkowski, T. (1991). A procedure for quantitatively comparing the syntactic coverage of English grammars. In *Proceedings DARPA Speech and Natural Language Workshop*, Pacific Grove, CA, pp. 306–311.
- Black, E., Jelinek, F., Lafferty, J. D., Magerman, D. M., Mercer, R. L., and Roukos, S. (1992). Towards history-based grammars: Using richer models for probabilistic parsing. In *Proceedings DARPA Speech and Natural Language Workshop*, Harriman, NY, pp. 134–139.
- Blunsom, P. and Baldwin, T. (2006). Multilingual deep lexical acquisition for hpsgs via supertagging. In *EMNLP 2006*.
- Bod, R. (1993). Using an annotated corpus as a stochastic grammar. In *EACL-93*, pp. 37–44.
- Booth, T. L. (1969). Probabilistic representation of formal languages. In *IEEE Conference Record of the 1969 Tenth Annual Symposium on Switching and Automata Theory*, pp. 74–81.
- Booth, T. L. and Thompson, R. A. (1973). Applying probability measures to abstract languages. *IEEE Transactions on Computers*, C-22(5), 442–450.
- Brill, E. and Resnik, P. (1994). A rule-based approach to prepositional phrase attachment disambiguation. In *COLING-94*, Kyoto, pp. 1198–1204.
- Briscoe, T. and Carroll, J. (1993). Generalized probabilistic LR parsing of natural language (corpora) with unification-based grammars. *Computational Linguistics*, 19(1), 25–59.
- Carroll, G. and Charniak, E. (1992). Two experiments on learning probabilistic dependency grammars from corpora. Tech. rep. CS-92-16, Brown University.
- Carroll, J., Briscoe, T., and Sanfilippo, A. (1998). Parser evaluation: A survey and a new proposal. In *LREC-98*, Granada, Spain, pp. 447–454.
- Charniak, E. (1997). Statistical parsing with a context-free grammar and word statistics. In *AAAI-97*, pp. 598–603. AAAI Press.
- Charniak, E. (2000). A maximum-entropy-inspired parser. In *NAACL 2000*, Seattle, Washington, pp. 132–139.
- Charniak, E. (2001). Immediate-head parsing for language models. In *ACL-01*, Toulouse, France.
- Charniak, E. and Johnson, M. (2005). Coarse-to-fine n -best parsing and MaxEnt discriminative reranking. In *ACL-05*, Ann Arbor.
- Chelba, C. and Jelinek, F. (2000). Structured language modeling. *Computer Speech and Language*, 14, 283–332.
- Clark, A. (2001). The unsupervised induction of stochastic context-free grammars using distributional clustering. In *CoNLL-01*.
- Clark, S. and Curran, J. R. (2004a). The importance of supertagging for wide-coverage CCG parsing. In *COLING-04*, pp. 282–288.
- Clark, S. and Curran, J. R. (2004b). Parsing the WSJ using CCG and log-linear models. In *ACL-04*, pp. 104–111.
- Collins, M. (1996). A new statistical parser based on bigram lexical dependencies. In *ACL-96*, Santa Cruz, CA, pp. 184–191.
- Collins, M. (1999). *Head-Driven Statistical Models for Natural Language Parsing*. Ph.D. thesis, University of Pennsylvania, Philadelphia.
- Collins, M. (2000). Discriminative reranking for natural language parsing. In *ICML 2000*, Stanford, CA, pp. 175–182.
- Collins, M. (2003). Head-driven statistical models for natural language parsing. *Computational Linguistics*, 29(4), 589–637.
- Collins, M., Hajič, J., Ramshaw, L. A., and Tillmann, C. (1999). A statistical parser for Czech. In *ACL-99*, College Park, MA, pp. 505–512.
- Collins, M. and Koo, T. (2005). Discriminative reranking for natural language parsing. *Computational Linguistics*, 31(1), 25–69.
- Eisner, J. (1996a). An empirical comparison of probability models for dependency grammar. Tech. rep. IRCS-96-11, Institute for Research in Cognitive Science, Univ. of Pennsylvania.
- Eisner, J. (1996b). Three new probabilistic models for dependency parsing: An exploration. In *COLING-96*, Copenhagen, pp. 340–345.
- Eisner, J. (2000). Bilexical grammars and their cubic-time parsing algorithms. In Bunt, H. and Nijholt, A. (Eds.), *Advances in Probabilistic and Other Parsing Technologies*, pp. 29–62. Kluwer.
- Francis, H. S., Gregory, M. L., and Michaelis, L. A. (1999). Are lexical subjects deviant?. In *CLS-99*. University of Chicago.

- Franz, A. (1997). Independence assumptions considered harmful. In *ACL/EACL-97*, Madrid, Spain, pp. 182–189.
- Givón, T. (1990). *Syntax: A Functional Typological Introduction*. John Benjamins.
- Goodman, J. (1997). Probabilistic feature grammars. In *IWPT-97*.
- Haghighi, A. and Klein, D. (2006). Prototype-driven grammar induction. In *COLING/ACL 2006*, pp. 881–888.
- Hale, J. (2001). A probabilistic earley parser as a psycholinguistic model. In *NAACL 2001*, pp. 159–166.
- Hall, K. and Johnson, M. (2003). Language modeling using efficient best-first bottom-up parsing. In *IEEE ASRU-03*, pp. 507–512.
- Hindle, D. and Rooth, M. (1990). Structural ambiguity and lexical relations. In *Proceedings DARPA Speech and Natural Language Workshop*, Hidden Valley, PA, pp. 257–262.
- Hindle, D. and Rooth, M. (1991). Structural ambiguity and lexical relations. In *ACL-91*, Berkeley, CA, pp. 229–236.
- Hockenmaier, J. and Steedman, M. (2002). Generative models for statistical parsing with Combinatory Categorical Grammar. In *ACL-02*, Philadelphia, PA.
- Horning, J. J. (1969). *A Study of Grammatical Inference*. Ph.D. thesis, Stanford University.
- Huang, L. and Chiang, D. (2005). Better k-best parsing. In *IWPT-05*, pp. 53–64.
- Jelinek, F. and Lafferty, J. D. (1991). Computation of the probability of initial substring generation by stochastic context-free grammars. *Computational Linguistics*, 17(3), 315–323.
- Jelinek, F., Lafferty, J. D., Magerman, D. M., Mercer, R. L., Ratnaparkhi, A., and Roukos, S. (1994). Decision tree parsing using a hidden derivation model. In *ARPA Human Language Technologies Workshop*, Plainsboro, N.J., pp. 272–277.
- Jiménez, V. M. and Marzal, A. (2000). Computation of the n best parse trees for weighted and stochastic context-free grammars. In *Advances in Pattern Recognition: Proceedings of the Joint IAPR International Workshops, SSPR 2000 and SPR 2000*, Alicante, Spain, pp. 183–192. Springer.
- Johnson, M. (1998). PCFG models of linguistic tree representations. *Computational Linguistics*, 24(4), 613–632.
- Johnson, M. (2001). Joint and conditional estimation of tagging and parsing models. In *ACL-01*, pp. 314–321.
- Johnson, M., Geman, S., Canon, S., Chi, Z., and Riezler, S. (1999). Estimators for stochastic “unification-based” grammars. In *ACL-99*, pp. 535–541.
- Joshi, A. K. and Srinivas, B. (1994). Disambiguation of super parts of speech (or supertags): Almost parsing. In *COLING-94*, Kyoto, pp. 154–160.
- Jurafsky, D., Wooters, C., Tajchman, G., Segal, J., Stolcke, A., Fosler, E., and Morgan, N. (1995). Using a stochastic context-free grammar as a language model for speech recognition. In *ICASSP-95*, pp. 189–192.
- Kaplan, R. M., Riezler, S., King, T. H., Maxwell III, J. T., Vasserman, A., and Crouch, R. (2004). Speed and accuracy in shallow and deep stochastic parsing. In *HLT-NAACL-04*.
- Klein, D. (2005). *The Unsupervised Learning of Natural Language Structure*. Ph.D. thesis, Stanford University.
- Klein, D. and Manning, C. D. (2001). Parsing and hypergraphs. In *IWPT-01*, pp. 123–134.
- Klein, D. and Manning, C. D. (2002). A generative constituent-context model for improved grammar induction. In *ACL-02*.
- Klein, D. and Manning, C. D. (2003a). A* parsing: Fast exact Viterbi parse selection. In *HLT-NAACL-03*.
- Klein, D. and Manning, C. D. (2003b). Accurate unlexicalized parsing. In *HLT-NAACL-03*.
- Klein, D. and Manning, C. D. (2003c). Fast exact inference with a factored model for natural language parsing. In Becker, S., Thrun, S., and Obermayer, K. (Eds.), *Advances in Neural Information Processing Systems 15*. MIT Press.
- Klein, D. and Manning, C. D. (2004). Corpus-based induction of syntactic structure: Models of dependency and constituency. In *ACL-04*, pp. 479–486.
- Kudo, T. and Matsumoto, Y. (2002). Japanese dependency analysis using cascaded chunking. In *CoNLL-02*, pp. 63–69.
- Lafferty, J. D., Sleator, D., and Temperley, D. (1992). Grammatical trigrams: A probabilistic model of link grammar. In *Proceedings of the 1992 AAAI Fall Symposium on Probabilistic Approaches to Natural Language*.
- Lari, K. and Young, S. J. (1990). The estimation of stochastic context-free grammars using the Inside-Outside algorithm. *Computer Speech and Language*, 4, 35–56.
- Levy, R. (2008). Expectation-based syntactic comprehension. *Cognition*, 106(3), 1126–1177.
- Lin, D. (1995). A dependency-based method for evaluating broad-coverage parsers. In *IJCAI-95*, Montreal, pp. 1420–1425.
- Magerman, D. M. and Marcus, M. P. (1991). Pearl: A probabilistic chart parser. In *EACL-91*, Berlin.
- Manning, C. D. and Schütze, H. (1999). *Foundations of Statistical Natural Language Processing*. MIT Press.
- Marcus, M. P. (1990). Summary of session 9: Automatic acquisition of linguistic structure. In *Proceedings DARPA Speech and Natural Language Workshop*, Hidden Valley, PA, pp. 249–250.
- Marcus, M. P., Santorini, B., and Marcinkiewicz, M. A. (1993). Building a large annotated corpus of English: The Penn treebank. *Computational Linguistics*, 19(2), 313–330.
- Matsuzaki, T., Miyao, Y., and Tsujii, J. (2007). Efficient HPSG parsing with supertagging and CFG-filtering. In *IJCAI-07*.
- McDonald, R., Crammer, K., and Pereira, F. C. N. (2005a). On-line large-margin training of dependency parsers. In *ACL-05*, Ann Arbor, pp. 91–98.
- McDonald, R., Pereira, F. C. N., Ribarov, K., and Hajič, J. (2005b). Non-projective dependency parsing using spanning tree algorithms. In *HLT-EMNLP-05*.

- Moscoso del Prado Martín, F., Kostic, A., and Baayen, R. H. (2004). Putting the bits together: An information theoretical perspective on morphological processing. *Cognition*, 94(1), 1–18.
- Ney, H. (1991). Dynamic programming parsing for context-free grammars in continuous speech recognition. *IEEE Transactions on Signal Processing*, 39(2), 336–340.
- Nivre, J. (2007). Incremental non-projective dependency parsing. In *NAACL-HLT 07*.
- Nivre, J., Hall, J., and Nilsson, J. (2006). Maltparser: A data-driven parser-generator for dependency parsing. In *LREC-06*, pp. 2216–2219.
- Petrov, S., Barrett, L., Thibaux, R., and Klein, D. (2006). Learning accurate, compact, and interpretable tree annotation. In *COLING/ACL 2006*, Sydney, Australia, pp. 433–440.
- Ratnaparkhi, A. (1996). A maximum entropy part-of-speech tagger. In *EMNLP 1996*, Philadelphia, PA, pp. 133–142.
- Ratnaparkhi, A., Reynar, J. C., and Roukos, S. (1994). A maximum entropy model for prepositional phrase attachment. In *ARPA Human Language Technologies Workshop*, Plainsboro, N.J., pp. 250–255.
- Resnik, P. (1992). Probabilistic tree-adjoining grammar as a framework for statistical natural language processing. In *COLING-92*, Nantes, France, pp. 418–424.
- Riezler, S., King, T. H., Kaplan, R. M., Crouch, R., Maxwell III, J. T., and Johnson, M. (2002). Parsing the Wall Street Journal using a Lexical-Functional Grammar and discriminative estimation techniques. In *ACL-02*, Philadelphia, PA.
- Roark, B. (2001). Probabilistic top-down parsing and language modeling. *Computational Linguistics*, 27(2), 249–276.
- Salomaa, A. (1969). Probabilistic and weighted grammars. *Information and Control*, 15, 529–544.
- Schabes, Y. (1990). *Mathematical and Computational Aspects of Lexicalized Grammars*. Ph.D. thesis, University of Pennsylvania, Philadelphia, PA.
- Schabes, Y. (1992). Stochastic lexicalized tree-adjoining grammars. In *COLING-92*, Nantes, France, pp. 426–433.
- Schabes, Y., Abeillé, A., and Joshi, A. K. (1988). Parsing strategies with ‘lexicalized’ grammars: Applications to Tree Adjoining Grammars. In *COLING-88*, Budapest, pp. 578–583.
- Schwartz, R. and Chow, Y.-L. (1990). The N-best algorithm: An efficient and exact procedure for finding the N most likely sentence hypotheses. In *ICASSP-90*, Vol. 1, pp. 81–84.
- Scott, M. and Shillcock, R. (2003). Eye movements reveal the on-line computation of lexical probabilities during reading. *Psychological Science*, 14(6), 648–652.
- Sekine, S. and Collins, M. (1997). The evalb software. <http://cs.nyu.edu/cs/projects/proteus/evalb>.
- Smith, D. A. and Eisner, J. (2007). Bootstrapping feature-rich dependency parsers with entropic priors. In *EMNLP/CoNLL 2007*, Prague, pp. 667–677.
- Smith, N. A. and Eisner, J. (2005). Guiding unsupervised grammar induction using contrastive estimation. In *IJCAI Workshop on Grammatical Inference Applications*, Edinburgh, pp. 73–82.
- Stetina, J. and Nagao, M. (1997). Corpus based PP attachment ambiguity resolution with a semantic dictionary. In Zhou, J. and Church, K. W. (Eds.), *Proceedings of the Fifth Workshop on Very Large Corpora*, Beijing, China, pp. 66–80.
- Stolcke, A. (1995). An efficient probabilistic context-free parsing algorithm that computes prefix probabilities. *Computational Linguistics*, 21(2), 165–202.
- Taskar, B., Klein, D., Collins, M., Koller, D., and Manning, C. D. (2004). Max-margin parsing. In *EMNLP 2004*, pp. 1–8.
- Titov, I. and Henderson, J. (2006). Loss minimization in parse reranking. In *EMNLP 2006*.
- Titov, I. and Henderson, J. (2007). A latent variable model for generative dependency parsing. In *IWPT-07*.
- Toutanova, K., Manning, C. D., Flickinger, D., and Oepen, S. (2005). Stochastic HPSG Parse Disambiguation using the Redwoods Corpus. *Research on Language & Computation*, 3(1), 83–105.
- van Rijsbergen, C. J. (1975). *Information Retrieval*. Butterworths.
- Witten, I. H. and Bell, T. C. (1991). The zero-frequency problem: Estimating the probabilities of novel events in adaptive text compression. *IEEE Transactions on Information Theory*, 37(4), 1085–1094.
- Xu, P., Chelba, C., and Jelinek, F. (2002). A study on richer syntactic dependencies for structured language modeling. In *ACL-02*, pp. 191–198.
- Yamada, H. and Matsumoto, Y. (2003). Statistical dependency analysis with support vector machines. In Noord, G. V. (Ed.), *IWPT-03*, pp. 195–206.
- Yuret, D. (1998). *Discovery of Linguistic Relations Using Lexical Attraction*. Ph.D. thesis, MIT.
- Zavrel, J. and Daelemans, W. (1997). Memory-based learning: Using similarity for smoothing. In *ACL/EACL-97*, Madrid, Spain, pp. 436–443.