

CHAPTER

F

Constituency Grammars

Because the Night by Bruce Springsteen and Patty Smith

The Fire Next Time by James Baldwin

If on a winter's night a traveler by Italo Calvino

Love Actually by Richard Curtis

Suddenly Last Summer by Tennessee Williams

A Scanner Darkly by Philip K. Dick

Six titles that are not constituents, from Geoffrey K. Pullum on Language Log (who was pointing out their incredible rarity).

syntax

The study of grammar has an ancient pedigree. The grammar of Sanskrit was described by the Indian grammarian Pāṇini sometime between the 7th and 4th centuries BCE, in his famous treatise the *Aṣṭādhyāyī* ('8 books'). And our word **syntax** comes from the Greek *sýntaxis*, meaning “setting out together or arrangement”, and refers to the way words are arranged together. We have seen various syntactic notions in previous chapters: ordering of sequences of words (Chapter 2), probabilities for these word sequences (Chapter 3), and the use of part-of-speech categories as a grammatical equivalence class for words (Chapter 17). In this chapter and the next three we introduce a variety of syntactic phenomena that go well beyond these simpler approaches, together with formal models for capturing them in a computationally useful manner.

The bulk of this chapter is devoted to context-free grammars. Context-free grammars are the backbone of many formal models of the syntax of natural language (and, for that matter, of computer languages). As such, they play a role in many computational applications, including grammar checking, semantic interpretation, dialogue understanding, and machine translation. They are powerful enough to express sophisticated relations among the words in a sentence, yet computationally tractable enough that efficient algorithms exist for parsing sentences with them (as we show in Chapter 18). Here we also introduce the concept of lexicalized grammars, focusing on one example, **combinatory categorial grammar**, or **CCG**.

In Chapter 19 we introduce a formal model of grammar called **syntactic dependencies** that is an alternative to these constituency grammars, and we'll give algorithms for **dependency parsing**. Both constituency and dependency formalisms are important for language processing.

Finally, we provide a brief overview of the grammar of English, illustrated from a domain with relatively simple sentences called ATIS (Air Traffic Information System) (Hemphill et al., 1990). ATIS systems were an early spoken language system for users to book flights, by expressing sentences like *I'd like to fly to Atlanta*.

F.1 Constituency

noun phrase

Syntactic constituency is the idea that groups of words can behave as single units, or constituents. Part of developing a grammar involves building an inventory of the constituents in the language. How do words group together in English? Consider the **noun phrase**, a sequence of words surrounding at least one noun. Here are some examples of noun phrases (thanks to Damon Runyon):

Harry the Horse
the Broadway coppers
they a high-class spot such as Mindy's
the reason he comes into the Hot Box
three parties from Brooklyn

What evidence do we have that these words group together (or “form constituents”)? One piece of evidence is that they can all appear in similar syntactic environments, for example, before a verb.

three parties from Brooklyn *arrive*...
a high-class spot such as Mindy's *attracts*...
the Broadway coppers *love*...
they *sit*

But while the whole noun phrase can occur before a verb, this is not true of each of the individual words that make up a noun phrase. The following are not grammatical sentences of English (recall that we use an asterisk (*) to mark fragments that are not grammatical English sentences):

*from *arrive*... *as *attracts*...
*the *is*... *spot *sat*...

Thus, to correctly describe facts about the ordering of these words in English, we must be able to say things like “*Noun Phrases can occur before verbs*”.

preposed Other kinds of evidence for constituency come from what are called **preposed** or **postposed** constructions. For example, the prepositional phrase *on September seventeenth* can be placed in a number of different locations in the following examples, including at the beginning (preposed) or at the end (postposed):

*On September seventeenth, I'd like to fly from Atlanta to Denver
I'd like to fly on September seventeenth from Atlanta to Denver
I'd like to fly from Atlanta to Denver on September seventeenth*

But again, while the entire phrase can be placed differently, the individual words making up the phrase cannot be:

- *On September, I'd like to fly seventeenth from Atlanta to Denver
- *On I'd like to fly September seventeenth from Atlanta to Denver
- *I'd like to fly on September from Atlanta to Denver seventeenth

F.2 Context-Free Grammars

The most widely used formal system for modeling constituent structure in English and other natural languages is the **Context-Free Grammar**, or **CFG**. Context-

free grammars are also called **Phrase-Structure Grammars**, and the formalism is equivalent to **Backus-Naur Form**, or **BNF**. The idea of basing a grammar on constituent structure dates back to the psychologist Wilhelm Wundt 1900 but was not formalized until Chomsky (1956) and, independently, Backus (1959).

rules

A context-free grammar consists of a set of **rules** or **productions**, each of which expresses the ways that symbols of the language can be grouped and ordered together, and a **lexicon** of words and symbols. For example, the following productions express that an **NP** (or **noun phrase**) can be composed of either a *ProperNoun* or a determiner (*Det*) followed by a *Nominal*; a *Nominal* in turn can consist of one or more *Nouns*.¹

lexicon

NP

$$\begin{aligned} NP &\rightarrow Det \ Nominal \\ NP &\rightarrow ProperNoun \\ Nominal &\rightarrow Noun \mid Nominal \ Noun \end{aligned}$$

Context-free rules can be hierarchically embedded, so we can combine the previous rules with others, like the following, that express facts about the lexicon:

$$\begin{aligned} Det &\rightarrow a \\ Det &\rightarrow the \\ Noun &\rightarrow flight \end{aligned}$$

terminal

non-terminal

The symbols that are used in a CFG are divided into two classes. The symbols that correspond to words in the language (“the”, “nightclub”) are called **terminal** symbols; the lexicon is the set of rules that introduce these terminal symbols. The symbols that express abstractions over these terminals are called **non-terminals**. In each context-free rule, the item to the right of the arrow (\rightarrow) is an ordered list of one or more terminals and non-terminals; to the left of the arrow is a single non-terminal symbol expressing some cluster or generalization. The non-terminal associated with each word in the lexicon is its lexical category, or part of speech.

A CFG can be thought of in two ways: as a device for generating sentences and as a device for assigning a structure to a given sentence. Viewing a CFG as a generator, we can read the \rightarrow arrow as “rewrite the symbol on the left with the string of symbols on the right”.

So starting from the symbol:

we can use our first rule to rewrite *NP* as:

and then rewrite *Nominal* as:

and finally rewrite these parts-of-speech as:

NP

Det Nominal

Noun

a flight

derivation

parse tree

dominates

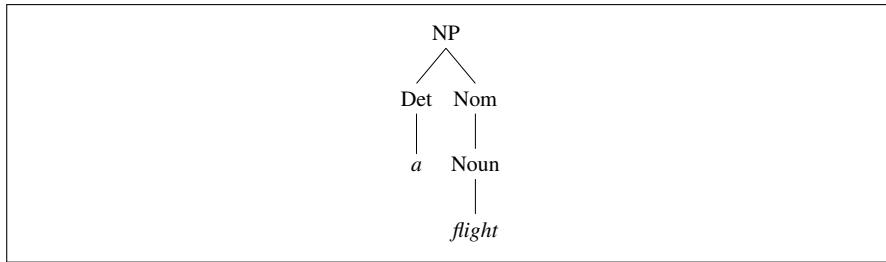
start symbol

We say the string *a flight* can be derived from the non-terminal *NP*. Thus, a CFG can be used to generate a set of strings. This sequence of rule expansions is called a **derivation** of the string of words. It is common to represent a derivation by a **parse tree** (commonly shown inverted with the root at the top). Figure F.1 shows the tree representation of this derivation.

In the parse tree shown in Fig. F.1, we can say that the node *NP* **dominates** all the nodes in the tree (*Det*, *Nom*, *Noun*, *a*, *flight*). We can say further that it immediately dominates the nodes *Det* and *Nom*.

The formal language defined by a CFG is the set of strings that are derivable from the designated **start symbol**. Each grammar must have one designated start

¹ When talking about these rules we can pronounce the rightarrow \rightarrow as “goes to”, and so we might read the first rule above as “NP goes to Det Nominal”.

**Figure F.1** A parse tree for “a flight”.

symbol, which is often called S . Since context-free grammars are often used to define sentences, S is usually interpreted as the “sentence” node, and the set of strings that are derivable from S is the set of sentences in some simplified version of English.

Let’s add a few additional rules to our inventory. The following rule expresses the fact that a sentence can consist of a noun phrase followed by a **verb phrase**:

$$S \rightarrow NP \ VP \quad I \text{ prefer a morning flight}$$

A verb phrase in English consists of a verb followed by assorted other things; for example, one kind of verb phrase consists of a verb followed by a noun phrase:

$$VP \rightarrow Verb \ NP \quad \text{prefer a morning flight}$$

Or the verb may be followed by a noun phrase and a prepositional phrase:

$$VP \rightarrow Verb \ NP \ PP \quad \text{leave Boston in the morning}$$

Or the verb phrase may have a verb followed by a prepositional phrase alone:

$$VP \rightarrow Verb \ PP \quad \text{leaving on Thursday}$$

A prepositional phrase generally has a preposition followed by a noun phrase. For example, a common type of prepositional phrase in the ATIS corpus is used to indicate location or direction:

$$PP \rightarrow Preposition \ NP \quad \text{from Los Angeles}$$

The NP inside a PP need not be a location; PPs are often used with times and dates, and with other nouns as well; they can be arbitrarily complex. Here are ten examples from the ATIS corpus:

to Seattle	on these flights
in Minneapolis	about the ground transportation in Chicago
on Wednesday	of the round trip flight on United Airlines
in the evening	of the AP fifty seven flight
on the ninth of July	with a stopover in Nashville

Figure F.2 gives a sample lexicon, and Fig. F.3 summarizes the grammar rules we’ve seen so far, which we’ll call \mathcal{L}_0 . Note that we can use the or-symbol $|$ to indicate that a non-terminal has alternate possible expansions.

We can use this grammar to generate sentences of this “ATIS-language”. We start with S , expand it to $NP \ VP$, then choose a random expansion of NP (let’s say, to I), and a random expansion of VP (let’s say, to $Verb \ NP$), and so on until we generate the string *I prefer a morning flight*. Figure F.4 shows a parse tree that represents a complete derivation of *I prefer a morning flight*.

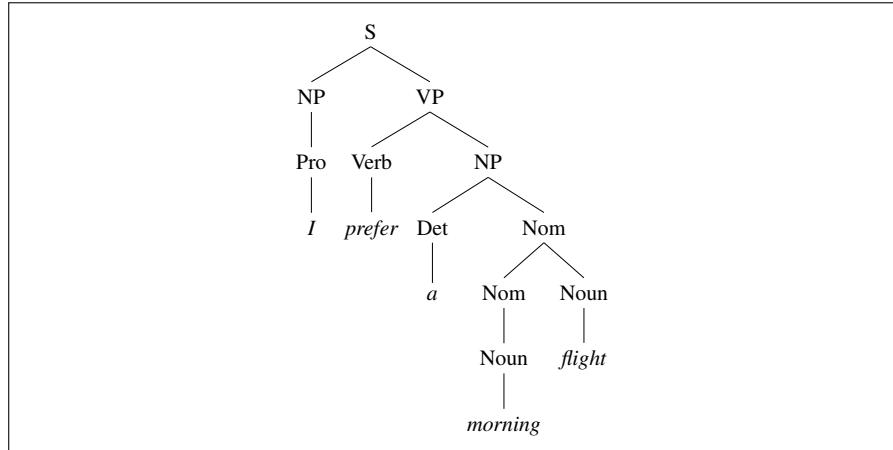
We can also represent a parse tree in a more compact format called **bracketed notation**; here is the bracketed representation of the parse tree of Fig. F.4:

bracketed notation

<i>Noun</i> \rightarrow flights flight breeze trip morning
<i>Verb</i> \rightarrow is prefer like need want fly do
<i>Adjective</i> \rightarrow cheapest non-stop first latest other direct
<i>Pronoun</i> \rightarrow me I you it
<i>Proper-Noun</i> \rightarrow Alaska Baltimore Los Angeles Chicago United American
<i>Determiner</i> \rightarrow the a an this these that
<i>Preposition</i> \rightarrow from to on near in
<i>Conjunction</i> \rightarrow and or but

Figure F.2 The lexicon for \mathcal{L}_0 .

Grammar Rules	Examples
$S \rightarrow NP VP$	I + want a morning flight
$NP \rightarrow Pronoun$	I
$ Proper-Noun$	Los Angeles
$ Det Nominal$	a + flight
$Nominal \rightarrow Nominal Noun$	morning + flight
$ Noun$	flights
$VP \rightarrow Verb$	do
$ Verb NP$	want + a flight
$ Verb NP PP$	leave + Boston + in the morning
$ Verb PP$	leaving + on Thursday
$PP \rightarrow Preposition NP$	from + Los Angeles

Figure F.3 The grammar for \mathcal{L}_0 , with example phrases for each rule.Figure F.4 The parse tree for “I prefer a morning flight” according to grammar \mathcal{L}_0 .

(F.1) $[S [NP [Pro I]] [VP [V prefer] [NP [Det a] [Nom [N morning] [Nom [N flight]]]]]]]$

A CFG like that of \mathcal{L}_0 defines a formal language. We saw in Chapter 2 that a formal language is a set of strings. Sentences (strings of words) that can be derived by a grammar are in the formal language defined by that grammar, and are called **grammatical** sentences. Sentences that cannot be derived by a given formal grammar are not in the language defined by that grammar and are referred to as **ungrammatical**.

grammatical
ungrammatical

generative grammar

This hard line between “in” and “out” characterizes all formal languages but is only a very simplified model of how natural languages really work. This is because determining whether a given sentence is part of a given natural language (say, English) often depends on the context. In linguistics, the use of formal languages to model natural languages is called **generative grammar** since the language is defined by the set of possible sentences “generated” by the grammar.

F.2.1 Formal Definition of Context-Free Grammar

We conclude this section with a quick, formal description of a context-free grammar and the language it generates. A context-free grammar G is defined by four parameters: N, Σ, R, S (technically this is a “4-tuple”).

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 $A \rightarrow \beta$, where A is a non-terminal,
	β is a string of symbols from the infinite set of strings $(\Sigma \cup N)^*$
S	a designated start symbol and a member of N

For the remainder of the book we adhere to the following conventions when discussing the formal properties of context-free grammars (as opposed to explaining particular facts about English or other languages).

Capital letters like A, B , and S	Non-terminals
S	The start symbol
Lower-case Greek letters like α, β , and γ	Strings drawn from $(\Sigma \cup N)^*$
Lower-case Roman letters like u, v , and w	Strings of terminals

A language is defined through the concept of derivation. One string derives another one if it can be rewritten as the second one by some series of rule applications. More formally, following [Hopcroft and Ullman \(1979\)](#),

directly derives

if $A \rightarrow \beta$ is a production of R and α and γ are any strings in the set $(\Sigma \cup N)^*$, then we say that $\alpha A \gamma$ **directly derives** $\alpha \beta \gamma$, or $\alpha A \gamma \Rightarrow \alpha \beta \gamma$.

Derivation is then a generalization of direct derivation:

Let $\alpha_1, \alpha_2, \dots, \alpha_m$ be strings in $(\Sigma \cup N)^*$, $m \geq 1$, such that

$$\alpha_1 \Rightarrow \alpha_2, \alpha_2 \Rightarrow \alpha_3, \dots, \alpha_{m-1} \Rightarrow \alpha_m$$

derives

We say that α_1 **derives** α_m , or $\alpha_1 \stackrel{*}{\Rightarrow} \alpha_m$.

We can then formally define the language \mathcal{L}_G generated by a grammar G as the set of strings composed of terminal symbols that can be derived from the designated start symbol S .

$$\mathcal{L}_G = \{w \mid w \text{ is in } \Sigma^* \text{ and } S \stackrel{*}{\Rightarrow} w\}$$

syntactic parsing

The problem of mapping from a string of words to its parse tree is called **syntactic parsing**; we define algorithms for constituency parsing in Chapter 18.

F.3 Some Grammar Rules for English

In this section, we introduce a few more aspects of the phrase structure of English; for consistency we will continue to focus on sentences from the ATIS domain. Because of space limitations, our discussion is necessarily limited to highlights. Readers are strongly advised to consult a good reference grammar of English, such as [Huddleston and Pullum \(2002\)](#).

F.3.1 Sentence-Level Constructions

In the small grammar \mathcal{L}_0 , we provided only one sentence-level construction for declarative sentences like *I prefer a morning flight*. Among the large number of constructions for English sentences, four are particularly common and important: declaratives, imperatives, yes-no questions, and wh-questions.

declarative

Sentences with **declarative** structure have a subject noun phrase followed by a verb phrase, like “I prefer a morning flight”. Sentences with this structure have a great number of different uses; here examples from the ATIS domain:

I want a flight from Ontario to Chicago
 The flight should be eleven a.m. tomorrow
 The return flight should leave at around seven p.m.

imperative

Sentences with **imperative** structure often begin with a verb phrase and have no subject. They are called imperative because they are almost always used for commands and suggestions; in the ATIS domain they are commands to the system.

Show the lowest fare
 Give me Sunday's flights arriving in Las Vegas from New York City
 List all flights between five and seven p.m.

We can model this sentence structure with another rule for the expansion of S :

$$S \rightarrow VP$$

yes-no question

Sentences with **yes-no question** structure are often (though not always) used to ask questions; they begin with an auxiliary verb, followed by a subject NP , followed by a VP . Here are some examples. Note that the third example is not a question at all but a request.

Do any of these flights have stops?
 Does American's flight eighteen twenty five serve dinner?
 Can you give me the same information for United?

Here's the rule:

$$S \rightarrow Aux NP VP$$

wh-phrase wh-word

The most complex sentence-level structures we examine here are the various **wh-**structures. These are so named because one of their constituents is a **wh-phrase**, that is, one that includes a **wh-word** (*who, whose, when, where, what, which, how, why*). These may be broadly grouped into two classes of sentence-level structures. The **wh-subject-question** structure is identical to the declarative structure, except that the first noun phrase contains some wh-word.

What airlines fly from Burbank to Denver?
 Which flights depart Burbank after noon and arrive in Denver by six p.m?
 Whose flights serve breakfast?

Here is a rule. Exercise F.7 discusses rules for the constituents that make up the *Wh-NP*.

$$S \rightarrow Wh\text{-}NP \ VP$$

wh-non-subject-question

In the **wh-non-subject-question** structure, the wh-phrase is not the subject of the sentence, and so the sentence includes another subject. In these types of sentences the auxiliary appears before the subject *NP*, just as in the yes-no question structures. Here is an example followed by a sample rule:

What flights do you have from Burbank to Tacoma Washington?

$$S \rightarrow Wh\text{-}NP \ Aux \ NP \ VP$$

long-distance dependencies

Constructions like the **wh-non-subject-question** contain what are called **long-distance dependencies** because the *Wh-NP* *what flights* is far away from the predicate that it is semantically related to, the main verb *have* in the *VP*. In some models of parsing and understanding compatible with the grammar rule above, long-distance dependencies like the relation between *flights* and *have* are thought of as a semantic relation. In such models, the job of figuring out that *flights* is the argument of *have* is done during semantic interpretation. Other models of parsing represent the relationship between *flights* and *have* as a syntactic relation, and the grammar is modified to insert a small marker called a **trace** or **empty category** after the verb. We discuss empty-category models when we introduce the Penn Treebank on page 15.

F.3.2 Clauses and Sentences

Before we move on, we should clarify the status of the *S* rules in the grammars we just described. *S* rules are intended to account for entire sentences that stand alone as fundamental units of discourse. However, *S* can also occur on the right-hand side of grammar rules and hence can be embedded within larger sentences. Clearly then, there's more to being an *S* than just standing alone as a unit of discourse.

clause

What differentiates sentence constructions (i.e., the *S* rules) from the rest of the grammar is the notion that they are in some sense *complete*. In this way they correspond to the notion of a **clause**, which traditional grammars often describe as forming a complete thought. One way of making this notion of “complete thought” more precise is to say an *S* is a node of the parse tree below which the main verb of the *S* has all of its **arguments**. We define verbal arguments later, but for now let's just see an illustration from the tree for *I prefer a morning flight* in Fig. F.4 on page 5. The verb *prefer* has two arguments: the subject *I* and the object *a morning flight*. One of the arguments appears below the *VP* node, but the other one, the subject *NP*, appears only below the *S* node.

F.3.3 The Noun Phrase

Our \mathcal{L}_0 grammar introduced three of the most frequent types of noun phrases that occur in English: pronouns, proper nouns and the $NP \rightarrow Det \ Nominal$ construction. The central focus of this section is on the last type since that is where the bulk of the syntactic complexity resides. These noun phrases consist of a head, the central noun in the noun phrase, along with various modifiers that can occur before or after the head noun. Let's take a close look at the various parts.

The Determiner

Noun phrases can begin with simple lexical determiners:

a stop	the flights	this flight
those flights	any flights	some flights

The role of the determiner can also be filled by more complex expressions:

United's flight	United's pilot's union	Denver's mayor's mother's canceled flight
-----------------	------------------------	---

In these examples, the role of the determiner is filled by a possessive expression consisting of a noun phrase followed by an 's as a possessive marker, as in the following rule.

$$Det \rightarrow NP\ 's$$

The fact that this rule is recursive (since an *NP* can start with a *Det*) helps us model the last two examples above, in which a sequence of possessive expressions serves as a determiner.

Under some circumstances determiners are optional in English. For example, determiners may be omitted if the noun they modify is plural:

(F.2) Show me *flights* from San Francisco to Denver on weekdays

As we saw in Chapter 17, **mass nouns** also don't require determination. Recall that mass nouns often (not always) involve something that is treated like a substance (including e.g., *water* and *snow*), don't take the indefinite article "a", and don't tend to pluralize. Many abstract nouns are mass nouns (*music*, *homework*). Mass nouns in the ATIS domain include *breakfast*, *lunch*, and *dinner*:

(F.3) Does this flight serve dinner?

The Nominal

The nominal construction follows the determiner and contains any pre- and post-head noun modifiers. As indicated in grammar \mathcal{L}_0 , in its simplest form a nominal can consist of a single noun.

$$Nominal \rightarrow Noun$$

As we'll see, this rule also provides the basis for the bottom of various recursive rules used to capture more complex nominal constructions.

Before the Head Noun

cardinal
numbers
ordinal
numbers
quantifiers

A number of different kinds of word classes can appear before the head noun but after the determiner (the "postdeterminers") in a nominal. These include **cardinal numbers**, **ordinal numbers**, **quantifiers**, and **adjectives**. Examples of cardinal numbers:

two friends	one stop
-------------	----------

Ordinal numbers include *first*, *second*, *third*, and so on, but also words like *next*, *last*, *past*, *other*, and *another*:

the first one	the next day	the second leg
the last flight	the other American flight	

Some quantifiers (*many*, *(a) few*, *several*) occur only with plural count nouns:

many fares

Adjectives occur after quantifiers but before nouns.

a <i>first-class</i> fare	a <i>non-stop</i> flight
the <i>longest</i> layover	the <i>earliest</i> lunch flight

adjective phrase

Adjectives can also be grouped into a phrase called an **adjective phrase** or AP. APs can have an adverb before the adjective (see Chapter 17 for definitions of adjectives and adverbs):

the *least expensive* fare

After the Head Noun

A head noun can be followed by **postmodifiers**. Three kinds of nominal postmodifiers are common in English:

prepositional phrases	all flights <i>from Cleveland</i>
non-finite clauses	any flights <i>arriving after eleven a.m.</i>
relative clauses	a flight <i>that serves breakfast</i>

They are especially common in the ATIS corpus since they are used to mark the origin and destination of flights.

Here are some examples of prepositional phrase postmodifiers, with brackets inserted to show the boundaries of each PP; note that two or more PPs can be strung together within a single NP:

all flights [*from Cleveland*] [*to Newark*]
 arrival [*in San Jose*] [*before seven p.m.*]
 a reservation [*on flight six oh six*] [*from Tampa*] [*to Montreal*]

Here's a new nominal rule to account for postnominal PPs:

Nominal → *Nominal PP*

non-finite

The three most common kinds of **non-finite** postmodifiers are the gerundive (-*ing*), *-ed*, and infinitive forms.

gerundive

Gerundive postmodifiers are so called because they consist of a verb phrase that begins with the gerundive (-*ing*) form of the verb. Here are some examples:

any of those [*leaving on Thursday*]
 any flights [*arriving after eleven a.m.*]
 flights [*arriving within thirty minutes of each other*]

We can define the *Nominals* with gerundive modifiers as follows, making use of a new non-terminal *GerundVP*:

Nominal → *Nominal GerundVP*

We can make rules for *GerundVP* constituents by duplicating all of our VP productions, substituting *GerundV* for *V*.

GerundVP → *GerundV NP*
 | *GerundV PP* | *GerundV* | *GerundV NP PP*

GerundV can then be defined as

GerundV → *being* | *arriving* | *leaving* | ...

The phrases in italics below are examples of the two other common kinds of non-finite clauses, infinitives and *-ed* forms:

the last flight *to arrive in Boston*
 I need to have dinner *served*
 Which is the aircraft *used by this flight?*

relative pronoun A postnominal relative clause (more correctly a **restrictive relative clause**), is a clause that often begins with a **relative pronoun** (*that* and *who* are the most common). The relative pronoun functions as the subject of the embedded verb in the following examples:

a flight *that serves breakfast*
 flights *that leave in the morning*
 the one *that leaves at ten thirty five*

We might add rules like the following to deal with these:

$$\begin{aligned} \text{Nominal} &\rightarrow \text{Nominal RelClause} \\ \text{RelClause} &\rightarrow (\text{who} \mid \text{that}) \text{ VP} \end{aligned}$$

The relative pronoun may also function as the object of the embedded verb, as in the following example; we leave for the reader the exercise of writing grammar rules for more complex relative clauses of this kind.

the earliest American Airlines flight *that I can get*

Various postnominal modifiers can be combined:

a flight [*from Phoenix to Detroit*] [*leaving Monday evening*]
 evening flights [*from Nashville to Houston*] [*that serve dinner*]
 a friend [*living in Denver*] [*that would like to visit me in DC*]

Before the Noun Phrase

predeterminers Word classes that modify and appear before *NPs* are called **predeterminers**. Many of these have to do with number or amount; a common predeterminer is *all*:

all the flights all flights all non-stop flights

The example noun phrase given in Fig. F.5 illustrates some of the complexity that arises when these rules are combined.

F.3.4 The Verb Phrase

The verb phrase consists of the verb and a number of other constituents. In the simple rules we have built so far, these other constituents include *NPs* and *PPs* and combinations of the two:

$$\begin{aligned} \text{VP} &\rightarrow \text{Verb disappear} \\ \text{VP} &\rightarrow \text{Verb NP prefer a morning flight} \\ \text{VP} &\rightarrow \text{Verb NP PP leave Boston in the morning} \\ \text{VP} &\rightarrow \text{Verb PP leaving on Thursday} \end{aligned}$$

sentential complements

Verb phrases can be significantly more complicated than this. Many other kinds of constituents, such as an entire embedded sentence, can follow the verb. These are called **sentential complements**:

You [VP [V said [S you had a two hundred sixty-six dollar fare]]]
 [VP [V Tell] [NP me] [S how to get from the airport to downtown]]
 I [VP [V think [S I would like to take the nine thirty flight]]]

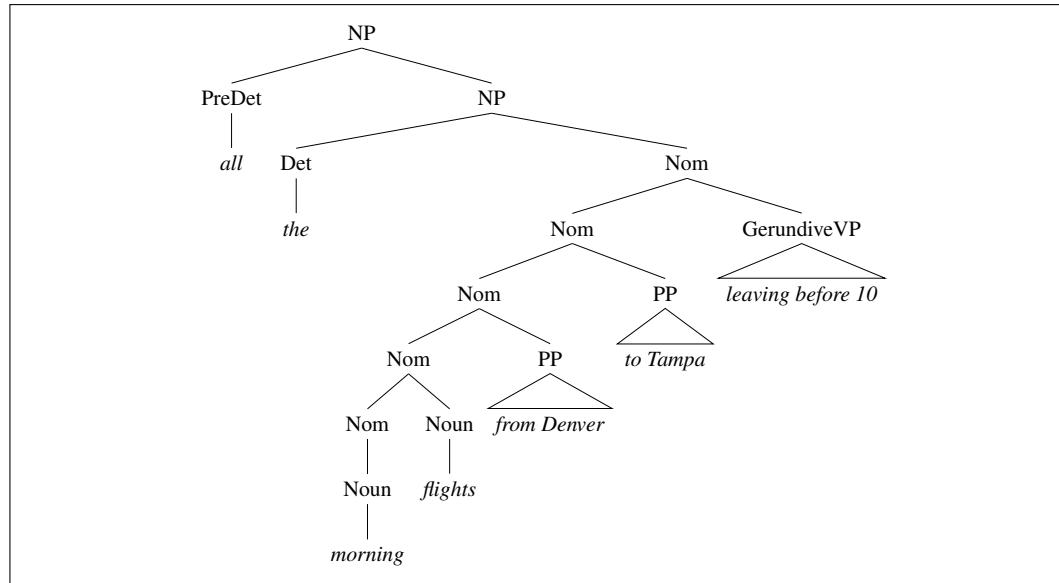


Figure F.5 A parse tree for “all the morning flights from Denver to Tampa leaving before 10”.

Here's a rule for these:

$$VP \rightarrow Verb\ S$$

Similarly, another potential constituent of the *VP* is another *VP*. This is often the case for verbs like *want*, *would like*, *try*, *intend*, *need*:

I want [*VP* to fly from Milwaukee to Orlando]
 Hi, I want [*VP* to arrange three flights]

While a verb phrase can have many possible kinds of constituents, not every verb is compatible with every verb phrase. For example, the verb *want* can be used either with an *NP* complement (*I want a flight*...) or with an infinitive *VP* complement (*I want to fly to*...). By contrast, a verb like *find* cannot take this sort of *VP* complement (**I found to fly to Dallas*).

This idea that verbs are compatible with different kinds of complements is a very old one; traditional grammar distinguishes between **transitive** verbs like *find*, which take a direct object *NP* (*I found a flight*), and **intransitive** verbs like *disappear*, which do not (**I disappeared a flight*).

transitive
intransitive
subcategorize
subcategorizes for
complements
subcategorization frame

Where traditional grammars **subcategorize** verbs into these two categories (transitive and intransitive), modern grammars distinguish as many as 100 subcategories. We say that a verb like *find* **subcategorizes for** an *NP*, and a verb like *want* subcategorizes for either an *NP* or a non-finite *VP*. We also call these constituents the **complements** of the verb (hence our use of the term **sentential complement** above). So we say that *want* can take a *VP* complement. These possible sets of complements are called the **subcategorization frame** for the verb. Another way of talking about the relation between the verb and these other constituents is to think of the verb as a logical predicate and the constituents as logical arguments of the predicate. So we can think of such predicate-argument relations as *FIND(I, A FLIGHT)* or *WANT(I, TO FLY)*. We talk more about this view of verbs and arguments in Appendix F when we talk about predicate calculus representations of verb semantics. Subcategorization frames for a set of example verbs are given in Fig. F.6.

Frame	Verb	Example
\emptyset	eat, sleep	I ate
NP	prefer, find, leave	Find [NP the flight from Pittsburgh to Boston]
$NP\ NP$	show, give	Show [NP me] [NP airlines with flights from Pittsburgh]
$PP_{from}\ PP_{to}$	fly, travel	I would like to fly [PP from Boston] [PP to Philadelphia]
$NP\ PP_{with}$	help, load	Can you help [NP me] [PP with a flight]
VP_{to}	prefer, want, need	I would prefer [VP_{to} to go by United Airlines]
S	mean	Does this mean [S AA has a hub in Boston]

Figure F.6 Subcategorization frames for a set of example verbs.

We can capture the association between verbs and their complements by making separate subtypes of the class Verb (e.g., *Verb-with-NP-complement*, *Verb-with-Inf-VP-complement*, *Verb-with-S-complement*, and so on):

$$\begin{aligned} \text{Verb-with-NP-complement} &\rightarrow \text{find} \mid \text{leave} \mid \text{repeat} \mid \dots \\ \text{Verb-with-S-complement} &\rightarrow \text{think} \mid \text{believe} \mid \text{say} \mid \dots \\ \text{Verb-with-Inf-VP-complement} &\rightarrow \text{want} \mid \text{try} \mid \text{need} \mid \dots \end{aligned}$$

Each VP rule could then be modified to require the appropriate verb subtype:

$$\begin{aligned} VP &\rightarrow \text{Verb-with-no-complement} \text{ disappear} \\ VP &\rightarrow \text{Verb-with-NP-comp } NP \text{ prefer a morning flight} \\ VP &\rightarrow \text{Verb-with-S-comp } S \text{ said there were two flights} \end{aligned}$$

A problem with this approach is the significant increase in the number of rules and the associated loss of generality.

F.3.5 Coordination

conjunctions
coordinate

The major phrase types discussed here can be conjoined with **conjunctions** like *and*, *or*, and *but* to form larger constructions of the same type. For example, a **coordinate** noun phrase can consist of two other noun phrases separated by a conjunction:

Please repeat [NP [NP the flights] *and* [NP the costs]]
I need to know [NP [NP the aircraft] *and* [NP the flight number]]

Here's a rule that allows these structures:

$$NP \rightarrow NP \text{ and } NP$$

Note that the ability to form coordinate phrases through conjunctions is often used as a test for constituency. Consider the following examples, which differ from the ones given above in that they lack the second determiner.

Please repeat the [Nom [Nom flights] *and* [Nom costs]]
I need to know the [Nom [Nom aircraft] *and* [Nom flight number]]

The fact that these phrases can be conjoined is evidence for the presence of the underlying *Nominal* constituent we have been making use of. Here's a rule for this:

$$Nominal \rightarrow Nominal \text{ and } Nominal$$

The following examples illustrate conjunctions involving VPs and Ss .

What flights do you have [VP [VP leaving Denver] *and* [VP arriving in San Francisco]]

[S [S I'm interested in a flight from Dallas to Washington] *and* [S I'm also interested in going to Baltimore]]

The rules for VP and S conjunctions mirror the NP one given above.

$$\begin{aligned} VP &\rightarrow VP \text{ and } VP \\ S &\rightarrow S \text{ and } S \end{aligned}$$

Since all the major phrase types can be conjoined in this fashion, it is also possible to represent this conjunction fact more generally; a number of grammar formalisms such as GPSG (Gazdar et al., 1985) do this using **metarules** like:

$$X \rightarrow X \text{ and } X$$

This metarule states that any non-terminal can be conjoined with the same non-terminal to yield a constituent of the same type; the variable X must be designated as a variable that stands for any non-terminal rather than a non-terminal itself.

F.4 Treebanks

Sufficiently robust grammars consisting of context-free grammar rules can be used to assign a parse tree to any sentence. This means that it is possible to build a corpus where every sentence in the collection is paired with a corresponding parse tree. Such a syntactically annotated corpus is called a **treebank**. Treebanks play an important role in parsing, as we discuss in Chapter 18, as well as in linguistic investigations of syntactic phenomena.

Penn Treebank A wide variety of treebanks have been created, generally through the use of parsers (of the sort described in the next few chapters) to automatically parse each sentence, followed by the use of humans (linguists) to hand-correct the parses. The **Penn Treebank** project (whose POS tagset we introduced in Chapter 17) has produced treebanks from the Brown, Switchboard, ATIS, and *Wall Street Journal* corpora of English, as well as treebanks in Arabic and Chinese. A number of treebanks use the dependency representation we will introduce in Chapter 19, including many that are part of the **Universal Dependencies** project (Nivre et al., 2016).

F.4.1 Example: The Penn Treebank Project

Figure F.7 shows sentences from the Brown and ATIS portions of the Penn Treebank.² Note the formatting differences for the part-of-speech tags; such small differences are common and must be dealt with in processing treebanks. The Penn Treebank part-of-speech tagset was defined in Chapter 17. The use of LISP-style parenthesized notation for trees is extremely common and resembles the bracketed notation we saw earlier in (F.1). For those who are not familiar with it we show a standard node-and-line tree representation in Fig. F.8.

Figure F.9 shows a tree from the *Wall Street Journal*. This tree shows another feature of the Penn Treebanks: the use of **traces** (-NONE- nodes) to mark long-distance

² The Penn Treebank project released treebanks in multiple languages and in various stages; for example, there were Treebank I (Marcus et al., 1993), Treebank II (Marcus et al., 1994), and Treebank III releases of English treebanks. We use Treebank III for our examples.

<code>((S (NP-SBJ (DT That) (JJ cold) (, ,) (JJ empty) (NN sky)) (VP (VBD was) (ADJP-PRD (JJ full) (PP (IN of) (NP (NN fire) (CC and) (NN light))))) (., .)))</code>	(a)	<code>((S (NP-SBJ The/DT flight/NN) (VP should/MD (VP arrive/VB (PP-TMP at/IN (NP eleven/CD a.m./RB)) (NP-TMP tomorrow/NN)))))</code>	(b)
---	-----	--	-----

Figure F.7 Parsed sentences from the LDC Treebank3 version of the (a) Brown and (b) ATIS corpora.

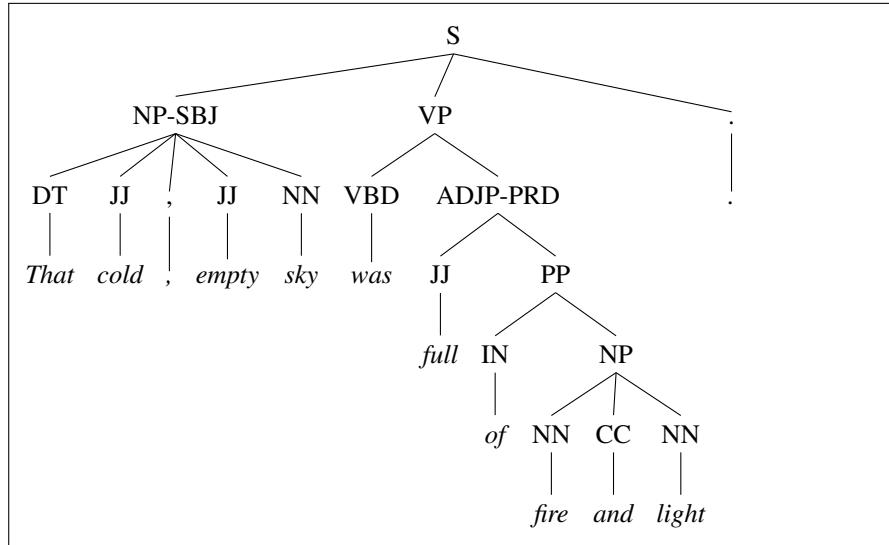


Figure F.8 The tree corresponding to the Brown corpus sentence in the previous figure.

syntactic movement

dependencies or **syntactic movement**. For example, quotations often follow a quotative verb like *say*. But in this example, the quotation “We would have to wait until we have collected on those assets” precedes the words *he said*. An empty *S* containing only the node -NONE- marks the position after *said* where the quotation sentence often occurs. This empty node is marked (in Treebanks II and III) with the index 2, as is the quotation *S* at the beginning of the sentence. Such co-indexing may make it easier for some parsers to recover the fact that this fronted or topicalized quotation is the complement of the verb *said*. A similar -NONE- node marks the fact that there is no syntactic subject right before the verb *to wait*; instead, the subject is the earlier *NP We*. Again, they are both co-indexed with the index 1.

The Penn Treebank II and Treebank III releases added further information to make it easier to recover the relationships between predicates and arguments. Certain phrases were marked with tags indicating the grammatical function of the phrase (as surface subject, logical topic, cleft, non-VP predicates) its presence in particular text categories (headlines, titles), and its semantic function (temporal phrases, lo-

```

( (S (‘ ‘ ‘)
  (S-TPC-2
    (NP-SBJ-1 (PRP We) )
    (VP (MD would)
      (VP (VB have)
        (S
          (NP-SBJ (-NONE- *-1) )
          (VP (TO to)
            (VP (VB wait)
              (SBAR-TMP (IN until)
                (S
                  (NP-SBJ (PRP we) )
                  (VP (VBP have)
                    (VP (VBN collected)
                      (PP-CLR (IN on)
                        (NP (DT those)(NNS assets))))))))))))
        (, ,) (‘ ‘ ‘)
        (NP-SBJ (PRP he) )
        (VP (VBD said)
          (S (-NONE- *T*-2) ))
        (..) )
      )
    )
  )
)

```

Figure F.9 A sentence from the *Wall Street Journal* portion of the LDC Penn Treebank. Note the use of the empty -NONE- nodes.

cations) (Marcus et al. 1994, Bies et al. 1995). Figure F.9 shows examples of the -SBJ (surface subject) and -TMP (temporal phrase) tags. Figure F.8 shows in addition the -PRD tag, which is used for predicates that are not VPs (the one in Fig. F.8 is an ADJP). We’ll return to the topic of grammatical function when we consider dependency grammars and parsing in Chapter 19.

F.4.2 Treebanks as Grammars

The sentences in a treebank implicitly constitute a grammar of the language represented by the corpus being annotated. For example, from the three parsed sentences in Fig. F.7 and Fig. F.9, we can extract each of the CFG rules in them. For simplicity, let’s strip off the rule suffixes (-SBJ and so on). The resulting grammar is shown in Fig. F.10.

The grammar used to parse the Penn Treebank is relatively flat, resulting in very many and very long rules. For example, among the approximately 4,500 different rules for expanding VPs are separate rules for PP sequences of any length and every possible arrangement of verb arguments:

```

VP → VBD PP
VP → VBD PP PP
VP → VBD PP PP PP
VP → VBD PP PP PP PP
VP → VB ADVP PP
VP → VB PP ADVP
VP → ADVB VB PP

```

as well as even longer rules, such as

```
VP → VBP PP PP PP PP PP ADVP PP
```

Grammar	Lexicon
$S \rightarrow NP VP.$	$PRP \rightarrow we \mid he$
$S \rightarrow NP VP$	$DT \rightarrow the \mid that \mid those$
$S \rightarrow "S", NP VP.$	$JJ \rightarrow cold \mid empty \mid full$
$S \rightarrow -NONE-$	$NN \rightarrow sky \mid fire \mid light \mid flight \mid tomorrow$
$NP \rightarrow DT NN$	$NN \rightarrow assets$
$NP \rightarrow DT NNS$	$CC \rightarrow and$
$NP \rightarrow NN CC NN$	$IN \rightarrow of \mid at \mid until \mid on$
$NP \rightarrow CD RB$	$CD \rightarrow eleven$
$NP \rightarrow DT JJ, JJ NN$	$RB \rightarrow a.m.$
$NP \rightarrow PRP$	$VB \rightarrow arrive \mid have \mid wait$
$NP \rightarrow -NONE-$	$VBD \rightarrow was \mid said$
$VP \rightarrow MD VP$	$VBP \rightarrow have$
$VP \rightarrow VBD ADJP$	$VBN \rightarrow collected$
$VP \rightarrow VBD S$	$MD \rightarrow should \mid would$
$VP \rightarrow VBN PP$	$TO \rightarrow to$
$VP \rightarrow VB S$	
$VP \rightarrow VB SBAR$	
$VP \rightarrow VBP VP$	
$VP \rightarrow VBN PP$	
$VP \rightarrow TO VP$	
$SBAR \rightarrow IN S$	
$ADJP \rightarrow JJ PP$	
$PP \rightarrow IN NP$	

Figure F.10 A sample of the CFG grammar rules and lexical entries that would be extracted from the three treebank sentences in Fig. F.7 and Fig. F.9.

which comes from the *VP* marked in italics:

This mostly happens because *we go from football in the fall to lifting in the winter to football again in the spring.*

Some of the many thousands of *NP* rules include

```

NP → DT JJ NN
NP → DT JJ NNS
NP → DT JJ NN NN
NP → DT JJ JJ NN
NP → DT JJ CD NNS
NP → RB DT JJ NN NN
NP → RB DT JJ JJ NNS
NP → DT JJ JJ NNP NNS
NP → DT NNP NNP NNP NNP JJ NN
NP → DT JJ NNP CC JJ JJ NN NNS
NP → RB DT JJS NN NN SBAR
NP → DT VBG JJ NNP NNP CC NNP
NP → DT JJ NNS , NNS CC NN NNS NN
NP → DT JJ JJ VBG NN NNP NNP FW NNP
NP → NP JJ , JJ " SBAR " NNS

```

The last two of those rules, for example, come from the following two noun phrases:

[_{DT} The] [_{JJ} state-owned] [_{JJ} industrial] [_{VBG} holding] [_{NN} company] [_{NNP} Instituto] [_{NNP} Nacional]
 [_{FW} de] [_{NNP} Industria]
 [_{NP} Shearson's] [_{JJ} easy-to-film], [_{JJ} black-and-white] “[_{SBAR} Where We Stand]” [_{NNS} commercials]

Viewed as a large grammar in this way, the Penn Treebank III *Wall Street Journal* corpus, which contains about 1 million words, also has about 1 million non-lexical rule tokens, consisting of about 17,500 distinct rule types.

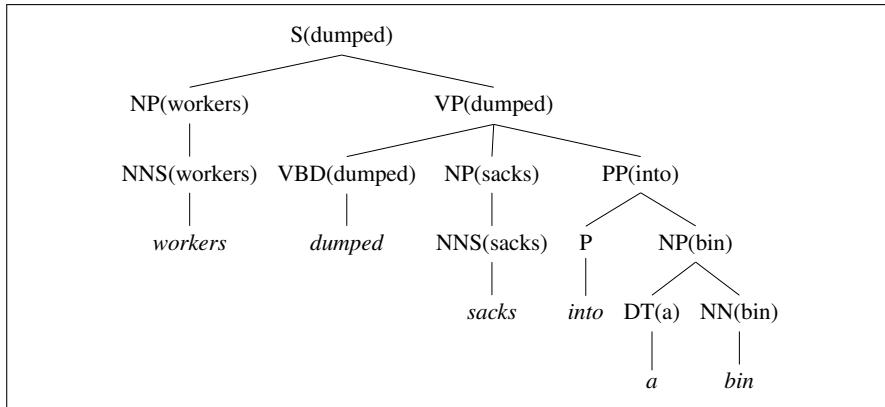


Figure F.11 A lexicalized tree from [Collins \(1999\)](#).

Various facts about the treebank grammars, such as their large numbers of flat rules, pose problems for probabilistic parsing algorithms. For this reason, it is common to make various modifications to a grammar extracted from a treebank. We discuss these further in Appendix C.

F.4.3 Heads and Head-Finding

We suggested informally earlier that syntactic constituents could be associated with a lexical **head**; N is the head of an NP , V is the head of a VP . This idea of a head for each constituent dates back to Bloomfield 1914, and is central to the dependency grammars and dependency parsing we'll introduce in Chapter 19. Heads are also important in probabilistic parsing (Appendix C) and in constituent-based grammar formalisms like Head-Driven Phrase Structure Grammar ([Pollard and Sag, 1994](#))..

In one simple model of lexical heads, each context-free rule is associated with a head ([Charniak 1997](#), [Collins 1999](#)). The head is the word in the phrase that is grammatically the most important. Heads are passed up the parse tree; thus, each non-terminal in a parse tree is annotated with a single word, which is its lexical head. Figure F.11 shows an example of such a tree from [Collins \(1999\)](#), in which each non-terminal is annotated with its head.

For the generation of such a tree, each CFG rule must be augmented to identify one right-side constituent to be the head child. The headword for a node is then set to the headword of its head child. Choosing these head children is simple for textbook examples (NN is the head of NP) but is complicated and indeed controversial for most phrases. (Should the complementizer *to* or the verb be the head of an infinite verb phrase?) Modern linguistic theories of syntax generally include a component that defines heads (see, e.g., ([Pollard and Sag, 1994](#))).

An alternative approach to finding a head is used in most practical computational systems. Instead of specifying head rules in the grammar itself, heads are identified dynamically in the context of trees for specific sentences. In other words, once a sentence is parsed, the resulting tree is walked to decorate each node with the appropriate head. Most current systems rely on a simple set of handwritten rules, such as a practical one for Penn Treebank grammars given in [Collins \(1999\)](#) but developed originally by [Magerman \(1995\)](#). For example, the rule for finding the head of an NP is as follows ([Collins, 1999](#), p. 238):

- If the last word is tagged POS, return last-word.

- Else search from right to left for the first child which is an NN, NNP, NNPS, NX, POS, or JJR.
- Else search from left to right for the first child which is an NP.
- Else search from right to left for the first child which is a \$, ADJP, or PRN.
- Else search from right to left for the first child which is a CD.
- Else search from right to left for the first child which is a JJ, JJS, RB or QP.
- Else return the last word

Selected other rules from this set are shown in Fig. F.12. For example, for VP rules of the form $VP \rightarrow Y_1 \dots Y_n$, the algorithm would start from the left of $Y_1 \dots Y_n$ looking for the first Y_i of type TO; if no TOs are found, it would search for the first Y_i of type VBD; if no VBDs are found, it would search for a VBN, and so on. See [Collins \(1999\)](#) for more details.

Parent	Direction	Priority List
ADJP	Left	NNS QP NN \$ ADVP JJ VBN VBG ADJP JJR NP JJS DT FW RBR RBS SBAR RB
ADVP	Right	RB RBR RBS FW ADVP TO CD JJR JJ IN NP JJS NN
PRN	Left	
PRT	Right	RP
QP	Left	\$ IN NNS NN JJ RB DT CD NCD QP JJR JJS
S	Left	TO IN VP S SBAR ADJP UCP NP
SBAR	Left	WHNP WHPP WHADVP WHADJP IN DT S SQ SINV SBAR FRAG
VP	Left	TO VBD VBN MD VBZ VB VBG VBP VP ADJP NN NNS NP

Figure F.12 Some head rules from [Collins \(1999\)](#). The head rules are also called a **head percolation table**.

F.5 Grammar Equivalence and Normal Form

A formal language is defined as a (possibly infinite) set of strings of words. This suggests that we could ask if two grammars are equivalent by asking if they generate the same set of strings. In fact, it is possible to have two distinct context-free grammars generate the same language.

We usually distinguish two kinds of grammar equivalence: **weak equivalence** and **strong equivalence**. Two grammars are strongly equivalent if they generate the same set of strings *and* if they assign the same phrase structure to each sentence (allowing merely for renaming of the non-terminal symbols). Two grammars are weakly equivalent if they generate the same set of strings but do not assign the same phrase structure to each sentence.

normal form

Chomsky normal form

binary branching

It is sometimes useful to have a **normal form** for grammars, in which each of the productions takes a particular form. For example, a context-free grammar is in **Chomsky normal form** (CNF) ([Chomsky, 1963](#)) if it is ϵ -free and if in addition each production is either of the form $A \rightarrow B \ C$ or $A \rightarrow a$. That is, the right-hand side of each rule either has two non-terminal symbols or one terminal symbol. Chomsky normal form grammars are **binary branching**, that is they have binary trees (down to the prelexical nodes). We make use of this binary branching property in the CKY parsing algorithm in Chapter 18.

Any context-free grammar can be converted into a weakly equivalent Chomsky normal form grammar. For example, a rule of the form

$$A \rightarrow B \ C \ D$$

can be converted into the following two CNF rules (Exercise F.?? asks the reader to formulate the complete algorithm):

$$\begin{aligned} A &\rightarrow B \ X \\ X &\rightarrow C \ D \end{aligned}$$

Sometimes using binary branching can actually produce smaller grammars. For example, the sentences that might be characterized as

$$VP \rightarrow VBD \ NP \ PP^*$$

are represented in the Penn Treebank by this series of rules:

$$\begin{aligned} VP &\rightarrow VBD \ NP \ PP \\ VP &\rightarrow VBD \ NP \ PP \ PP \\ VP &\rightarrow VBD \ NP \ PP \ PP \ PP \\ VP &\rightarrow VBD \ NP \ PP \ PP \ PP \ PP \\ &\dots \end{aligned}$$

but could also be generated by the following two-rule grammar:

$$\begin{aligned} VP &\rightarrow VBD \ NP \ PP \\ VP &\rightarrow VP \ PP \end{aligned}$$

The generation of a symbol A with a potentially infinite sequence of symbols B with a rule of the form $A \rightarrow A \ B$ is known as **Chomsky-adjunction**.

F.6 Summary

This chapter has introduced a number of fundamental concepts in syntax through the use of **context-free grammars**.

- In many languages, groups of consecutive words act as a group or a **constituent**, which can be modeled by **context-free grammars** (which are also known as **phrase-structure grammars**).
- A context-free grammar consists of a set of **rules** or **productions**, expressed over a set of **non-terminal** symbols and a set of **terminal** symbols. Formally, a particular **context-free language** is the set of strings that can be **derived** from a particular **context-free grammar**.
- A **generative grammar** is a traditional name in linguistics for a formal language that is used to model the grammar of a natural language.
- There are many sentence-level grammatical constructions in English; **declarative**, **imperative**, **yes-no question**, and **wh-question** are four common types; these can be modeled with context-free rules.
- An English **noun phrase** can have **determiners**, **numbers**, **quantifiers**, and **adjective phrases** preceding the **head noun**, which can be followed by a number of **postmodifiers**; **gerundive** and **infinitive** VPs are common possibilities.
- **Subjects** in English **agree** with the main verb in person and number.
- Verbs can be **subcategorized** by the types of **complements** they expect. Simple subcategories are **transitive** and **intransitive**; most grammars include many more categories than these.
- **Treebanks** of parsed sentences exist for many genres of English and for many languages. Treebanks can be searched with tree-search tools.

- Any context-free grammar can be converted to **Chomsky normal form**, in which the right-hand side of each rule has either two non-terminals or a single terminal.

Historical Notes

According to [Percival \(1976\)](#), the idea of breaking up a sentence into a hierarchy of constituents appeared in the *Völkerpsychologie* of the groundbreaking psychologist Wilhelm Wundt ([Wundt, 1900](#)):

...den sprachlichen Ausdruck für die willkürliche Gliederung einer Gesamtvorstellung in ihre in logische Beziehung zueinander gesetzten Bestandteile

[the linguistic expression for the arbitrary division of a total idea into its constituent parts placed in logical relations to one another]

Wundt's idea of constituency was taken up into linguistics by Leonard Bloomfield in his early book *An Introduction to the Study of Language* ([Bloomfield, 1914](#)). By the time of his later book, *Language* ([Bloomfield, 1933](#)), what was then called “immediate-constituent analysis” was a well-established method of syntactic study in the United States. By contrast, traditional European grammar, dating from the Classical period, defined relations between *words* rather than constituents, and European syntacticians retained this emphasis on such **dependency** grammars, the subject of Chapter 19.

American Structuralism saw a number of specific definitions of the immediate constituent, couched in terms of their search for a “discovery procedure”: a methodological algorithm for describing the syntax of a language. In general, these attempt to capture the intuition that “The primary criterion of the immediate constituent is the degree in which combinations behave as simple units” ([Bazell, 1952/1966](#), p. 284). The most well known of the specific definitions is Harris' idea of distributional similarity to individual units, with the *substitutability* test. Essentially, the method proceeded by breaking up a construction into constituents by attempting to substitute simple structures for possible constituents—if a substitution of a simple form, say, *man*, was substitutable in a construction for a more complex set (like *intense young man*), then the form *intense young man* was probably a constituent. Harris's test was the beginning of the intuition that a constituent is a kind of equivalence class.

The first formalization of this idea of hierarchical constituency was the **phrase-structure grammar** defined in [Chomsky \(1956\)](#) and further expanded upon (and argued against) in [Chomsky \(1957\)](#) and [Chomsky \(1956/1975\)](#). From this time on, most generative linguistic theories were based at least in part on context-free grammars or generalizations of them (such as Head-Driven Phrase Structure Grammar ([Pollard and Sag, 1994](#)), Lexical-Functional Grammar ([Bresnan, 1982](#)), the Minimalist Program ([Chomsky, 1995](#)), and Construction Grammar ([Kay and Fillmore, 1999](#)), *inter alia*); many of these theories used schematic context-free templates known as **X-bar schemata**, which also relied on the notion of syntactic head.

Shortly after Chomsky's initial work, the context-free grammar was reinvented by [Backus \(1959\)](#) and independently by [Naur et al. \(1960\)](#) in their descriptions of the ALGOL programming language; [Backus \(1996\)](#) noted that he was influenced by the productions of Emil Post and that Naur's work was independent of his (Backus')

own. After this early work, a great number of computational models of natural language processing were based on context-free grammars because of the early development of efficient algorithms to parse these grammars (see Chapter 18).

There are various classes of extensions to CFGs, many designed to handle long-distance dependencies in the syntax. (Other grammars instead treat long-distance-dependent items as being related semantically rather than syntactically (Kay and Fillmore 1999, Culicover and Jackendoff 2005).

One extended formalism is **Tree Adjoining Grammar** (TAG) (Joshi, 1985). The primary TAG data structure is the tree, rather than the rule. Trees come in two kinds: **initial trees** and **auxiliary trees**. Initial trees might, for example, represent simple sentential structures, and auxiliary trees add recursion into a tree. Trees are combined by two operations called **substitution** and **adjunction**. The adjunction operation handles long-distance dependencies. See Joshi (1985) for more details. Tree Adjoining Grammar is a member of the family of **mildly context-sensitive languages**.

We mentioned on page 15 another way of handling long-distance dependencies, based on the use of empty categories and co-indexing. The Penn Treebank uses this model, which draws (in various Treebank corpora) from the Extended Standard Theory and Minimalism (Radford, 1997).

Readers interested in the grammar of English should get one of the three large reference grammars of English: Huddleston and Pullum (2002), Biber et al. (1999), and Quirk et al. (1985).

There are many good introductory textbooks on syntax from different perspectives. Sag et al. (2003) is an introduction to syntax from a **generative** perspective, focusing on the use of phrase-structure rules, unification, and the type hierarchy in Head-Driven Phrase Structure Grammar. Van Valin, Jr. and La Polla (1997) is an introduction from a **functional** perspective, focusing on cross-linguistic data and on the functional motivation for syntactic structures.

Exercises

F.1 Draw tree structures for the following ATIS phrases:

1. Dallas
2. from Denver
3. after five p.m.
4. arriving in Washington
5. early flights
6. all redeye flights
7. on Thursday
8. a one-way fare
9. any delays in Denver

F.2 Draw tree structures for the following ATIS sentences:

1. Does American Airlines have a flight between five a.m. and six a.m.?
2. I would like to fly on American Airlines.
3. Please repeat that.
4. Does American 487 have a first-class section?
5. I need to fly between Philadelphia and Atlanta.
6. What is the fare from Atlanta to Denver?

7. Is there an American Airlines flight from Philadelphia to Dallas?

F.3 Assume a grammar that has many *VP* rules for different subcategorizations, as expressed in Section F.3.4, and differently subcategorized verb rules like *Verb-with-NP-complement*. How would the rule for postnominal relative clauses (F.4) need to be modified if we wanted to deal properly with examples like *the earliest flight that you have*? Recall that in such examples the pronoun *that* is the object of the verb *get*. Your rules should allow this noun phrase but should correctly rule out the ungrammatical *S *I get*.

F.4 Does your solution to the previous problem correctly model the NP *the earliest flight that I can get*? How about *the earliest flight that I think my mother wants me to book for her*? Hint: this phenomenon is called **long-distance dependency**.

F.5 Write rules expressing the verbal subcategory of English auxiliaries; for example, you might have a rule *verb-with-bare-stem-VP-complement → can*.

F.6 *NPs* like *Fortune's office* or *my uncle's marks* are called **possessive** or **genitive** noun phrases. We can model possessive noun phrases by treating the sub-NP like *Fortune's* or *my uncle's* as a determiner of the following head noun. Write grammar rules for English possessives. You may treat 's as if it were a separate word (i.e., as if there were always a space before 's).

F.7 Page 8 discussed the need for a *Wh-NP* constituent. The simplest *Wh-NP* is one of the *Wh-pronouns* (*who, whom, whose, which*). The *Wh*-words *what* and *which* can be determiners: *which four will you have?*, *what credit do you have with the Duke?* Write rules for the different types of *Wh-NPs*.

possessive
genitive

Backus, J. W. 1959. The syntax and semantics of the proposed international algebraic language of the Zurich ACM-GAMM Conference. *Information Processing: Proceedings of the International Conference on Information Processing, Paris*. UNESCO.

Backus, J. W. 1996. Transcript of question and answer session. In R. L. Wexelblat, ed., *History of Programming Languages*, page 162. Academic Press.

Bazell, C. E. 1952/1966. The correspondence fallacy in structural linguistics. In E. P. Hamp, F. W. Householder, and R. Austerlitz, eds, *Studies by Members of the English Department, Istanbul University (3), reprinted in Readings in Linguistics II* (1966), 271–298. University of Chicago Press.

Biber, D., S. Johansson, G. Leech, S. Conrad, and E. Finegan. 1999. *Longman Grammar of Spoken and Written English*. Pearson.

Bies, A., M. Ferguson, K. Katz, and R. MacIntyre. 1995. Bracketing guidelines for Treebank II style Penn Treebank Project.

Bloomfield, L. 1914. *An Introduction to the Study of Language*. Henry Holt and Company.

Bloomfield, L. 1933. *Language*. University of Chicago Press.

Bresnan, J., ed. 1982. *The Mental Representation of Grammatical Relations*. MIT Press.

Charniak, E. 1997. Statistical parsing with a context-free grammar and word statistics. *AAAI*.

Chomsky, N. 1956. Three models for the description of language. *IRE Transactions on Information Theory*, 2(3):113–124.

Chomsky, N. 1956/1975. *The Logical Structure of Linguistic Theory*. Plenum.

Chomsky, N. 1957. *Syntactic Structures*. Mouton.

Chomsky, N. 1963. Formal properties of grammars. In R. D. Luce, R. Bush, and E. Galanter, eds, *Handbook of Mathematical Psychology*, volume 2, 323–418. Wiley.

Chomsky, N. 1995. *The Minimalist Program*. MIT Press.

Collins, M. 1999. *Head-Driven Statistical Models for Natural Language Parsing*. Ph.D. thesis, University of Pennsylvania, Philadelphia.

Culicover, P. W. and R. Jackendoff. 2005. *Simpler Syntax*. Oxford University Press.

Gazdar, G., E. Klein, G. K. Pullum, and I. A. Sag. 1985. *Generalized Phrase Structure Grammar*. Blackwell.

Harris, Z. S. 1946. From morpheme to utterance. *Language*, 22(3):161–183.

Hemphill, C. T., J. Godfrey, and G. Doddington. 1990. *The ATIS spoken language systems pilot corpus*. *Speech and Natural Language Workshop*.

Hopcroft, J. E. and J. D. Ullman. 1979. *Introduction to Automata Theory, Languages, and Computation*. Addison-Wesley.

Huddleston, R. and G. K. Pullum. 2002. *The Cambridge Grammar of the English Language*. Cambridge University Press.

Joshi, A. K. 1985. Tree adjoining grammars: How much context-sensitivity is required to provide reasonable structural descriptions? In D. R. Dowty, L. Karttunen, and A. Zwicky, eds, *Natural Language Parsing*, 206–250. Cambridge University Press.

Kay, P. and C. J. Fillmore. 1999. Grammatical constructions and linguistic generalizations: The What's X Doing Y? construction. *Language*, 75(1):1–33.

Magerman, D. M. 1995. *Statistical decision-tree models for parsing*. *ACL*.

Marcus, M. P., G. Kim, M. A. Marcinkiewicz, R. MacIntyre, A. Bies, M. Ferguson, K. Katz, and B. Schasberger. 1994. *The Penn Treebank: Annotating predicate argument structure*. *HLT*.

Marcus, M. P., B. Santorini, and M. A. Marcinkiewicz. 1993. *Building a large annotated corpus of English: The Penn treebank*. *Computational Linguistics*, 19(2):313–330.

Naur, P., J. W. Backus, F. L. Bauer, J. Green, C. Katz, J. McCarthy, A. J. Perlis, H. Rutishauser, K. Samelson, B. Vauquois, J. H. Wegstein, A. van Wijnagaarden, and M. Woodger. 1960. Report on the algorithmic language ALGOL 60. *CACM*, 3(5):299–314. Revised in CACM 6:1, 1–17, 1963.

Nivre, J., M.-C. de Marneffe, F. Ginter, Y. Goldberg, J. Hajic̄, C. D. Manning, R. McDonald, S. Petrov, S. Pyysalo, N. Silveira, R. Tsarfaty, and D. Zeman. 2016. *Universal Dependencies v1: A multilingual treebank collection*. *LREC*.

Percival, W. K. 1976. On the historical source of immediate constituent analysis. In J. D. McCawley, ed., *Syntax and Semantics Volume 7, Notes from the Linguistic Underground*, 229–242. Academic Press.

Pollard, C. and I. A. Sag. 1994. *Head-Driven Phrase Structure Grammar*. University of Chicago Press.

Quirk, R., S. Greenbaum, G. Leech, and J. Svartvik. 1985. *A Comprehensive Grammar of the English Language*. Longman.

Radford, A. 1997. *Syntactic Theory and the Structure of English: A Minimalist Approach*. Cambridge University Press.

Sag, I. A., T. Wasow, and E. M. Bender, eds. 2003. *Syntactic Theory: A Formal Introduction*. CSLI Publications, Stanford, CA.

Van Valin, Jr., R. D. and R. La Polla. 1997. *Syntax: Structure, Meaning, and Function*. Cambridge University Press.

Wundt, W. 1900. *Völkerpsychologie: eine Untersuchung der Entwicklungsgesetze von Sprache, Mythos, und Sitten*. W. Engelmann, Leipzig. Band II: Die Sprache, Zweiter Teil.