Introduction to Parsing

Data Structures and Algorithms for Computational Linguistics III (ISCL-BA-07)

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What is parsing?

- *Parsing* is the task of analyzing a string of symbols to discover its (inherent) structure
- Typically, the structure (and the valid strings in the language) is defined by a *grammar*
- The output of a parser is a structured representation of the input string, often a tree
- *Recognition* is an intimately related task which determines whether a given string is in a language

Ingredients of a parser

(for natural language parsing)

- A formal grammar defining a language of interest
- An algorithm that (efficiently) verifies whether a given string is in the language (recognizer) and enumerates the grammar rules used for verification (parser)
- A system for ambiguity resolution (not in this course)

Grammars

- A grammar is a finite specification of a possibly infinite language

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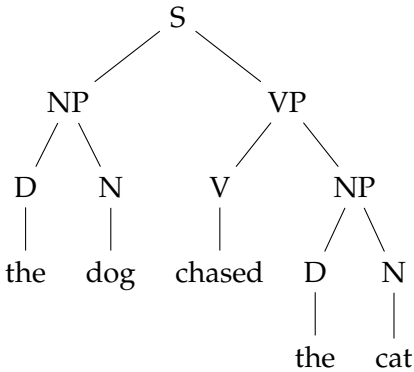
- A grammar is a finite specification of a possibly infinite language
- The most commonly studied type of grammars are *phrase structure grammars*

S → NP VP	NP → D N	VP → V NP	
V → chased	D → the	N → cat	N → dog

Grammars

- A grammar is a finite specification of a possibly infinite language
- The most commonly studied type of grammars are *phrase structure grammars*
- Analysis using context-free grammars result in *constituency* or *phrase structure* trees

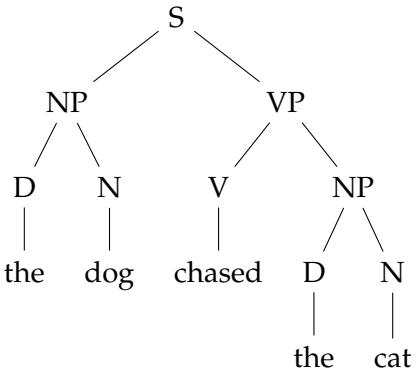


$S \rightarrow NP\ VP$ $\quad NP \rightarrow D\ N$ $\quad VP \rightarrow V\ NP$

$V \rightarrow$ chased $\quad D \rightarrow$ the $\quad N \rightarrow$ cat $\quad N \rightarrow$ dog

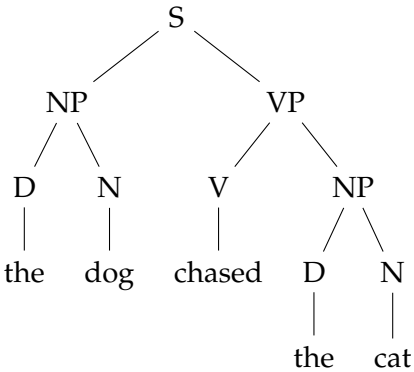
Why study parsing?

- In general, it is an intermediate step for interpreting sentences



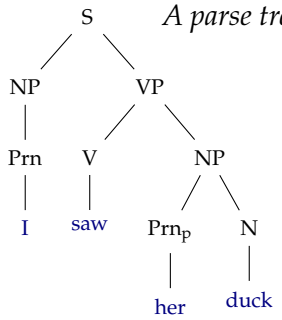
Why study parsing?

- In general, it is an intermediate step for interpreting sentences
- Applications include:
  - Compiler construction
  - Grammar checking
  - Sentiment analysis
  - Information (e.g., relation) extraction
  - Argument mining
  - ...



Different ways to represent a context-free parse

A parse tree

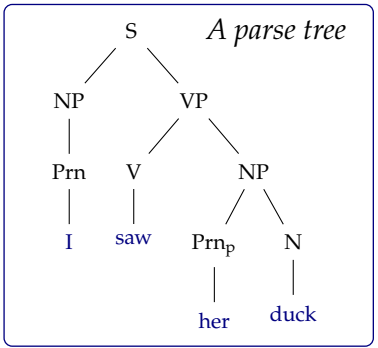


A history of derivations

Sentential form	derivation		
S		(start)	
NP VP	S	$\Rightarrow$	NP VP
Prn VP	NP	$\Rightarrow$	Prn
I VP	Prn	$\Rightarrow$	I
I V NP	VP	$\Rightarrow$	V NP
I saw NP	V	$\Rightarrow$	saw
I saw Prn$_p$ N	NP	$\Rightarrow$	Prn$_p$ N
I saw her N	Prn$_p$	$\Rightarrow$	her
I saw her duck	N	$\Rightarrow$	duck

(*Labeled*) *brackets*: $\Big[_{\text{S}}\Big[_{\text{NP}}\,[_{\text{Prn}}\ \text{I}]\Big]\Big[_{\text{VP}}\,[_{\text{V}}\ \text{saw}]\,\Big[_{\text{NP}}\,\Big[_{\text{Prn}_p}\ \text{her}\Big]\,[_{\text{N}}\ \text{duck}]\,\Big]\Big]\Big]$

Different ways to represent a context-free parse



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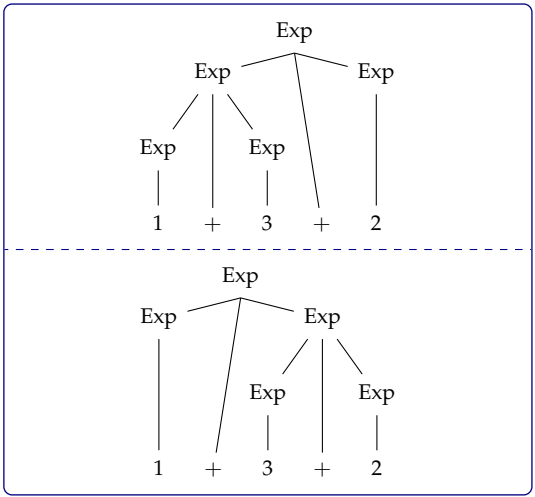
Relation between different representations

- The parse tree and the bracket representation is equivalent
  - parse trees are easier to read by humans
  - brackets are easier for computers
  - brackets are the typical representation for treebanks
- A parse tree (or bracket representation) can be obtained with a different order of production rules

Grammars and ambiguity

$$\text{Exp} \rightarrow \text{n}$$
$$\text{Exp} \rightarrow \text{Exp} + \text{Exp}$$
(terminal symbol 'n' stands for any number)

- If a grammar is ambiguous, some sentences produce multiple analyses
- If the resulting analysis lead to the same semantics, the ambiguity is *spurious*



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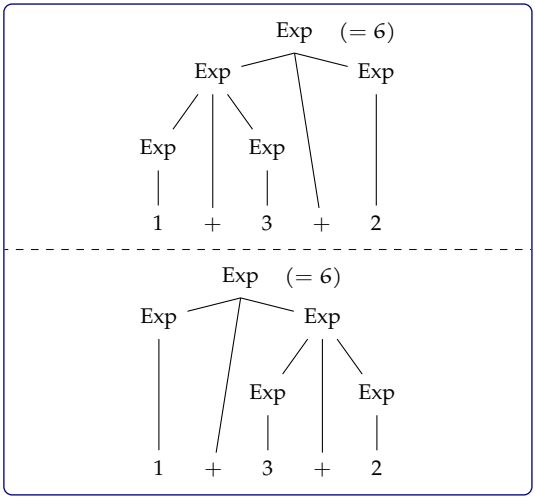

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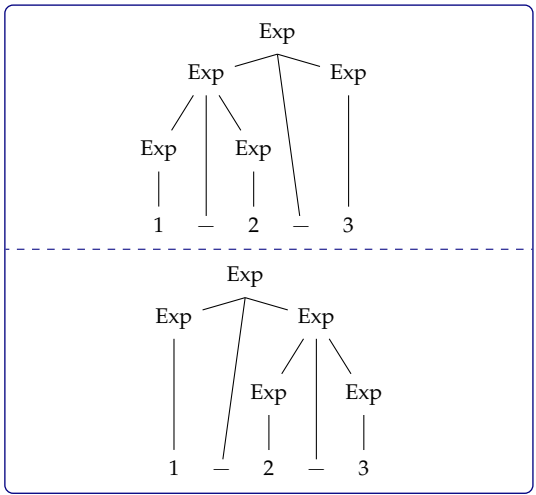
Grammars and ambiguity

$$\text{Exp} \rightarrow \text{n}$$
$$\text{Exp} \rightarrow \text{Exp} - \text{Exp}$$

(terminal symbol 'n' stands for any number)

- Is this ambiguity spurious?



Grammars and ambiguity

$$\begin{aligned} \text{Exp} &\rightarrow \text{n} \\ \text{Exp} &\rightarrow \text{Exp} - \text{Exp} \end{aligned}$$

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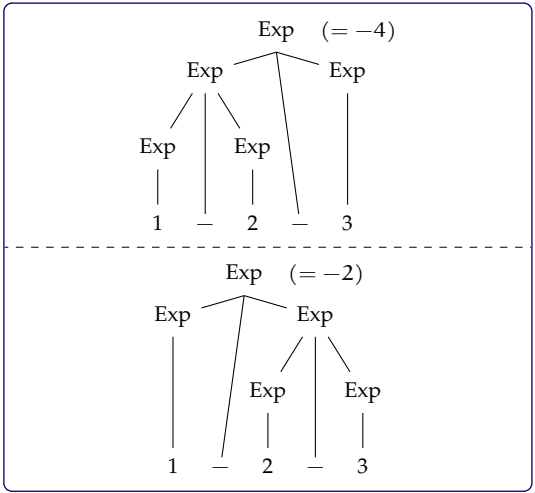
- Is this ambiguity spurious?
- If different structures yield different semantics, the ambiguity is *essential*



Ambiguity can be removed from a grammar

if the language is not ambiguous

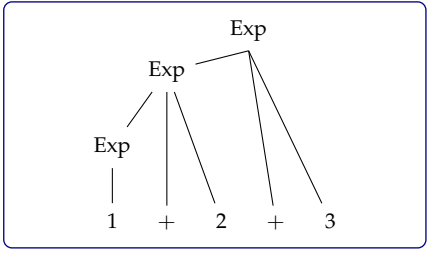
$$\begin{aligned} \text{Exp} &\rightarrow \text{n} \\ \text{Exp} &\rightarrow \text{Exp} + \text{n} \end{aligned}$$

(terminal symbol 'n' stands for any number)

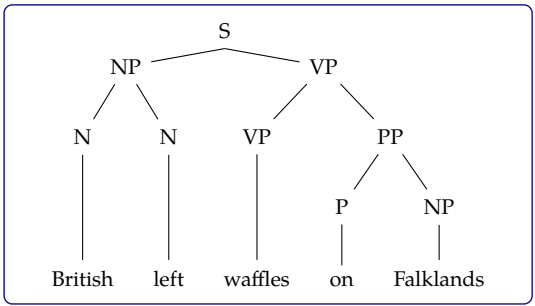
- The grammar above does not have the ambiguity of

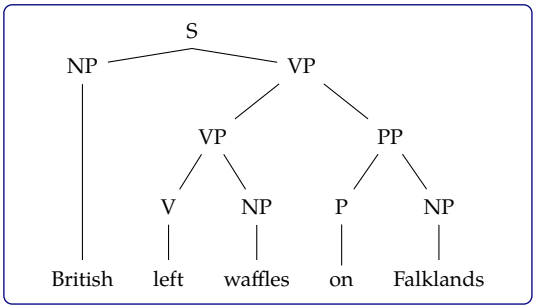
$$\begin{aligned} \text{Exp} &\rightarrow \text{n} \\ \text{Exp} &\rightarrow \text{Exp} + \text{Exp} \end{aligned}$$

- Both grammars define the same language



Natural languages are ambiguous





- The grammars we define have to distinguish between two different structures
- We need methods for ranking analyses

Top-down parsing

general idea

- Start from S, find a sequence of derivations that yield the sentence
- This is simply the same as the generation procedure we discussed earlier
- Attempt to generate all strings from a grammar, but allow only the productions that 'produce' the input string

Top-down: demonstration

the cat bites a dog

$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Top-down: demonstration

S

the cat bites a dog

S	$\rightarrow$	NP VP
NP	$\rightarrow$	Det N
VP	$\rightarrow$	V NP
VP	$\rightarrow$	V
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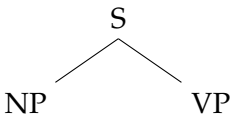

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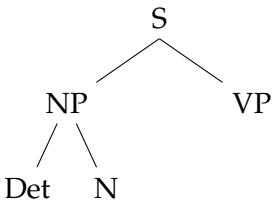

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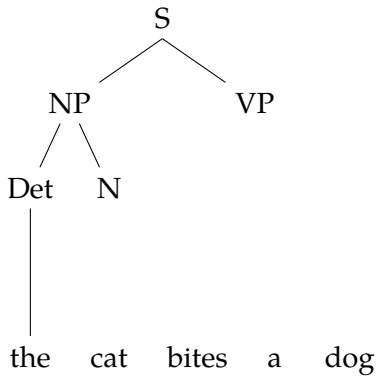

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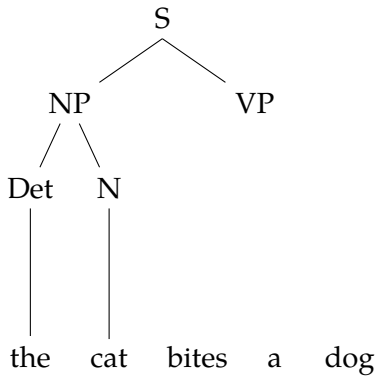

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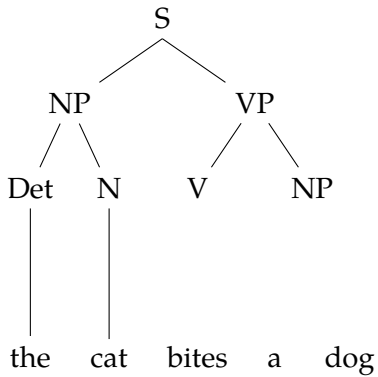

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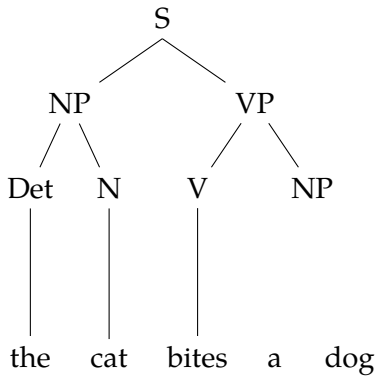

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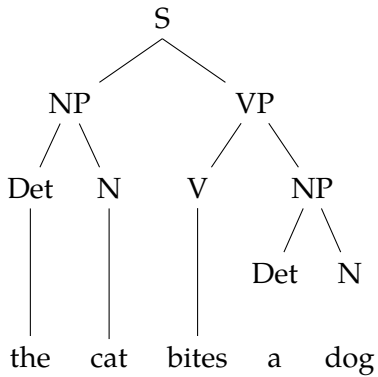

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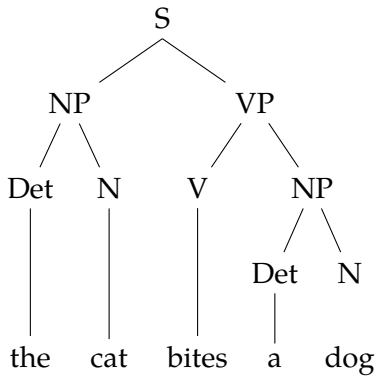

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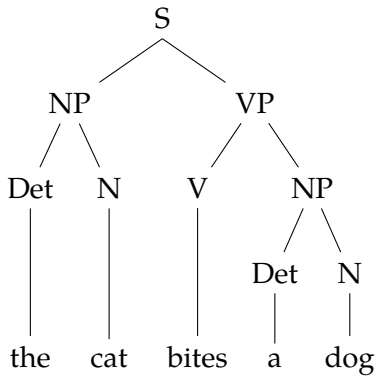

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From demonstration to parsing

- There may be multiple productions applicable
- We need an automatic mechanism to select the correct productions
- We have two actions:

  predict generate a hypothesis based on the grammar

  match when a terminal symbol is produced, check if it matches with the one in the expected position
    - if matched, continue
    - otherwise, backtrack
- if we eliminate all non terminals from the sentential form, and the complete input string is matched (produced), then parsing successful

Top-down parsing: another demonstration

the grammar

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VP	$\rightarrow$	V
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parse: *the cat bites a dog*

Top-down parsing: another demonstration

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matched	goal	production
	S	S ⇒ NP VP

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matched	goal	production
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	NP VP	NP ⇒ Det N

Top-down parsing: another demonstration

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	Det N VP	Det ⇒ a ✗

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the cat	VP	VP ⇒ V

Top-down parsing: another demonstration

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the cat	VP	VP ⇒ V
the cat bites	V	V ⇒ bites ✓
the cat bites		(not at the end) ✗

Top-down parsing: another demonstration

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the cat	VP	VP ⇒ V NP

Top-down parsing: another demonstration

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the cat	VP	VP ⇒ V
the cat bites	V	V ⇒ bites ✓
the cat bites		(not at the end) ✗
the cat	VP	VP ⇒ V NP
the cat	V NP	V ⇒ bites ✓

Top-down parsing: another demonstration

the grammar

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the cat	VP	VP ⇒ V
the cat bites	V	V ⇒ bites ✓
the cat bites		(not at the end) ✗
the cat	VP	VP ⇒ V NP
the cat	V NP	V ⇒ bites ✓
the cat bites	Det N	NP ⇒ Det N

Top-down parsing: another demonstration

the grammar

S	→	NP VP
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VP	→	V NP
VP	→	V
Det	→	a
Det	→	the
N	→	cat
N	→	dog
V	→	bites

parse: *the cat bites a dog*

matched	goal	production
	S	S ⇒ NP VP
	NP VP	NP ⇒ Det N
	Det N VP	Det ⇒ a ✗
	Det N VP	Det ⇒ the ✓
the	N VP	N ⇒ dog ✗
the cat	N VP	N ⇒ cat ✓
the cat	VP	VP ⇒ V
the cat bites	V	V ⇒ bites ✓
the cat bites		(not at the end) ✗
the cat	VP	VP ⇒ V NP
the cat	V NP	V ⇒ bites ✓
the cat bites	Det N	NP ⇒ Det N
the cat bites a	N	Det ⇒ a ✓

Top-down parsing: another demonstration

the grammar

S	→	NP VP
NP	→	Det N
VP	→	V NP
VP	→	V
Det	→	a
Det	→	the
N	→	cat
N	→	dog
V	→	bites

parse: *the cat bites a dog*

matched	goal	production
	S	S ⇒ NP VP
	NP VP	NP ⇒ Det N
	Det N VP	Det ⇒ a ✗
	Det N VP	Det ⇒ the ✓
the	N VP	N ⇒ dog ✗
the cat	N VP	N ⇒ cat ✓
the cat	VP	VP ⇒ V
the cat bites	V	V ⇒ bites ✓
the cat bites		(not at the end) ✗
the cat	VP	VP ⇒ V NP
the cat	V NP	V ⇒ bites ✓
the cat bites	Det N	NP ⇒ Det N
the cat bites a	N	Det ⇒ a ✓
the cat bites a dog		Det ⇒ dog ✓

Top-down parsing: another demonstration

the grammar

S	→	NP VP
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the	N VP	N ⇒ dog ✗
the cat	N VP	N ⇒ cat ✓
the cat	VP	VP ⇒ V
the cat bites	V	V ⇒ bites ✓
the cat bites		(not at the end) ✗
the cat	VP	VP ⇒ V NP
the cat	V NP	V ⇒ bites ✓
the cat bites	Det N	NP ⇒ Det N
the cat bites a	N	Det ⇒ a ✓
the cat bites a dog		Det ⇒ dog ✓

Note that the valid productions yield the parse tree.

Top-down parsing: problems and possible solutions

- The trial-and-error procedure leads to exponential time parsing

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Top-down parsing: problems and possible solutions

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Top-down parsing: problems and possible solutions

- The trial-and-error procedure leads to exponential time parsing
- But lots of repeated work: dynamic programming may help avoid it
- What happens if we had a rule like

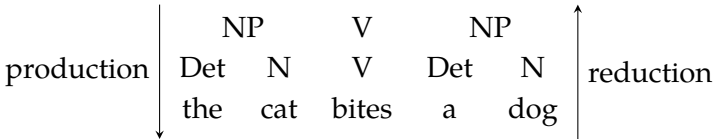
$$\text{NP} \rightarrow \text{NP PP}$$

  some rules may cause infinite loops
- Notice that if we knew which terminals are possible as the initial part of a non-terminal symbol, we can eliminate the unsuccessful matches earlier

Bottom-up parsing

general idea

- Start from from the input symbols, and try to *reduce* the input to start symbol
- We need to match parts of the sentential form (starting from the input) to the RHS of the grammar rules
- While top-down process relies on *productions* the bottom-up process relies on *reductions*

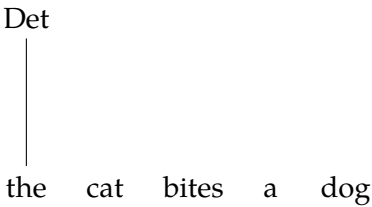


Bottom-up: demonstration

the cat bites a dog

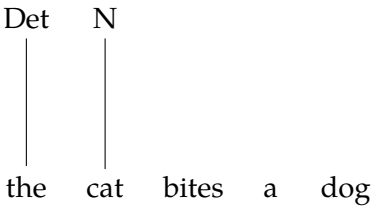
$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



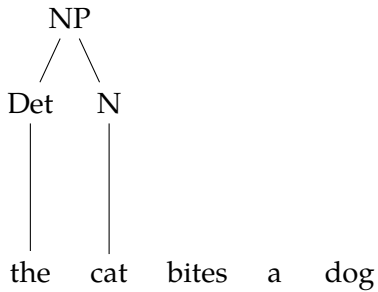
$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow \text{the} \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



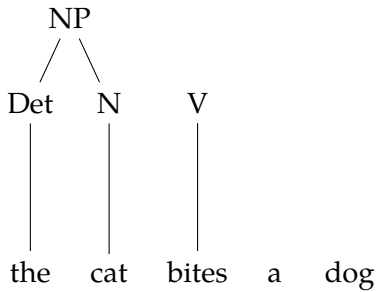
$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



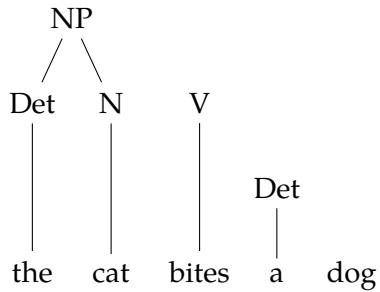
$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
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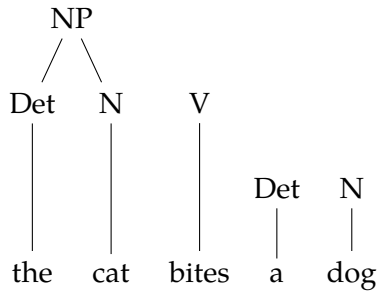
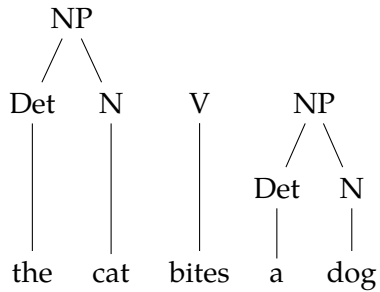
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



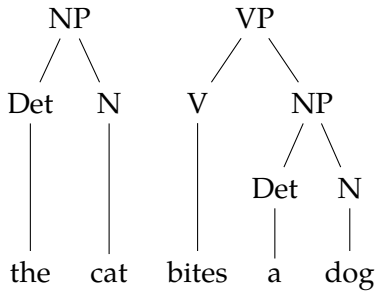
$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



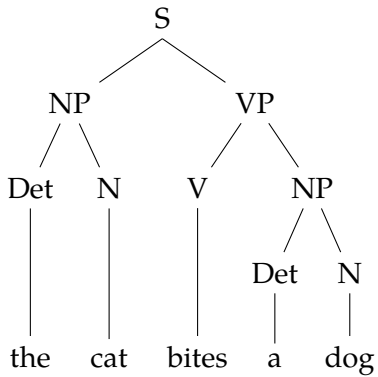
$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

Bottom-up: demonstration



$$
\begin{aligned}
S &\rightarrow NP\ VP \\
NP &\rightarrow Det\ N \\
VP &\rightarrow V\ NP \\
VP &\rightarrow V \\
Det &\rightarrow a \\
Det &\rightarrow the \\
N &\rightarrow cat \\
N &\rightarrow dog \\
V &\rightarrow bites
\end{aligned}
$$

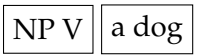
Bottom-up: demonstration



$$
\begin{aligned}
S &\rightarrow \text{NP VP} \\
NP &\rightarrow \text{Det N} \\
VP &\rightarrow \text{V NP} \\
VP &\rightarrow \text{V} \\
Det &\rightarrow \text{a} \\
Det &\rightarrow \text{the} \\
N &\rightarrow \text{cat} \\
N &\rightarrow \text{dog} \\
V &\rightarrow \text{bites}
\end{aligned}
$$

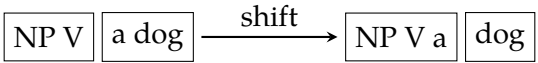
A (first) introduction to shift-reduce parsing

- We keep two data structures:
  - a stack for the (partially) reduced sentential form
  - an input queue that contains only terminal symbols

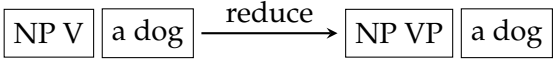


- We use two operations:

  shift shifts a terminal to stack



  reduce when top symbols on stack mach a RHS, replace them with the LHS of the rule



Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog
S Det N		NP $\Rightarrow$ Det N

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog
S Det N		NP $\Rightarrow$ Det N
S NP		(stuck)

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog
S Det N		NP $\Rightarrow$ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog
S Det N		NP $\Rightarrow$ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift
NP V a	dog	Det $\Rightarrow$ a

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog
S Det N		NP $\Rightarrow$ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift
NP V a	dog	Det $\Rightarrow$ a
NP V Det	dog	shift

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog
S Det N		NP $\Rightarrow$ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift
NP V a	dog	Det $\Rightarrow$ a
NP V Det	dog	shift
NP V Det dog		N $\Rightarrow$ dog

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det ⇒ the
Det	cat bites a dog	shift
Det cat	bites a dog	N ⇒ cat
Det N	bites a dog	NP ⇒ Det N
NP	bites a dog	shift
NP bites	a dog	V ⇒ bites
NP V	a dog	VP ⇒ V
NP VP	a dog	S ⇒ NP VP
S	a dog	shift
S a	dog	Det ⇒ A
S Det dog		N ⇒ dog
S Det N		NP ⇒ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift
NP V a	dog	Det ⇒ a
NP V Det	dog	shift
NP V Det dog		N ⇒ dog
NP V Det N		NP ⇒ Det N

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det ⇒ the
Det	cat bites a dog	shift
Det cat	bites a dog	N ⇒ cat
Det N	bites a dog	NP ⇒ Det N
NP	bites a dog	shift
NP bites	a dog	V ⇒ bites
NP V	a dog	VP ⇒ V
NP VP	a dog	S ⇒ NP VP
S	a dog	shift
S a	dog	Det ⇒ A
S Det dog		N ⇒ dog
S Det N		NP ⇒ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift
NP V a	dog	Det ⇒ a
NP V Det	dog	shift
NP V Det dog		N ⇒ dog
NP V Det N		NP ⇒ Det N
NP V NP		VP ⇒ V NP

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det $\Rightarrow$ the
Det	cat bites a dog	shift
Det cat	bites a dog	N $\Rightarrow$ cat
Det N	bites a dog	NP $\Rightarrow$ Det N
NP	bites a dog	shift
NP bites	a dog	V $\Rightarrow$ bites
NP V	a dog	VP $\Rightarrow$ V
NP VP	a dog	S $\Rightarrow$ NP VP
S	a dog	shift
S a	dog	Det $\Rightarrow$ A
S Det dog		N $\Rightarrow$ dog
S Det N		NP $\Rightarrow$ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift
NP V a	dog	Det $\Rightarrow$ a
NP V Det	dog	shift
NP V Det dog		N $\Rightarrow$ dog
NP V Det N		NP $\Rightarrow$ Det N
NP V NP		VP $\Rightarrow$ V NP
NP VP		S $\Rightarrow$ NP VP

Shift-reduce (bottom-up) parsing a demonstration

stack	input	rule
	the cat bites a dog	shift
the	cat bites a dog	Det ⇒ the
Det	cat bites a dog	shift
Det cat	bites a dog	N ⇒ cat
Det N	bites a dog	NP ⇒ Det N
NP	bites a dog	shift
NP bites	a dog	V ⇒ bites
NP V	a dog	VP ⇒ V
NP VP	a dog	S ⇒ NP VP
S	a dog	shift
S a	dog	Det ⇒ A
S Det dog		N ⇒ dog
S Det N		NP ⇒ Det N
S NP		(stuck)

stack	input	rule
NP V	a dog	shift
NP V a	dog	Det ⇒ a
NP V Det	dog	shift
NP V Det dog		N ⇒ dog
NP V Det N		NP ⇒ Det N
NP V NP		VP ⇒ V NP
NP VP		S ⇒ NP VP
S		(done)

- All input reduced to S, accept
- Rules form the parse tree

Summary

- Parsing can be formulated as a top-down or bottom-up search (the search may also be depth-first or breadth first)
- Naive parsing algorithms are inefficient (exponential time complexity)
- There are some directions: dynamic programming, filtering
- Suggested reading (for constituency parsing): Jurafsky and Martin (2009, draft 3rd ed, chapters 12 & 13)
- A general reference for parsing: Grune and Jacobs (2007)

Summary

- Parsing can be formulated as a top-down or bottom-up search (the search may also be depth-first or breadth first)
- Naive parsing algorithms are inefficient (exponential time complexity)
- There are some directions: dynamic programming, filtering
- Suggested reading (for constituency parsing): Jurafsky and Martin (2009, draft 3rd ed, chapters 12 & 13)
- A general reference for parsing: Grune and Jacobs (2007)

Next:

- Bottom-up chart parsing: CKY algorithm
- Suggested reading: Jurafsky and Martin (2009, draft 3rd ed, section 13.2)

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