Hasso Plattner Institut
IT Systems Engineering | Universität Potsdam

Natural Language Processing

Parsing

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based on the slides of the course book

Parsing

- Finding structural relationship between words in a sentence

- Applications
  - Spell checking
  - Speech recognition
  - Machine translation
  - Language modeling

Outline

1. Phrase Structure
2. Syntactic Parsing
   - CKY Algorithm
3. Statistical Parsing

Outline

Constituency

- Working based on Constituency (Phrase structure)
  - Organizing words into nested constituents
  - Showing that groups of words within utterances can act as single units
  - Forming coherent classes from these units that can behave in similar ways
    - With respect to their internal structure
    - With respect to other units in the language
  - Considering a head word for each constituent

Constituency

the writer talked to the audiences about his new book.

the writer talked about his new book to the audiences. ✔

about his new book the writer talked to the audiences. ✔

the writer talked book to the audiences about his new. ✗

Context Free Grammar (CFG)

- Grammar G consists of
  - Terminals (T)
  - Non-terminals (N)
  - Start symbol (S)
  - Rules (R)

CFG

- Terminals
  - The set of words in the text
- Non-Terminals
  - The constituents in a language (noun phrase, verb phrase, ...)
- Start symbol
  - The main constituent of the language (sentence)
- Rules
  - Equations that consist of a single non-terminal on the left and any number of terminals and non-terminals on the right

CFG

$S \rightarrow NP \;\; VP$
$S \rightarrow VP$
$NP \rightarrow N$
$NP \rightarrow Det\ N$
$NP \rightarrow NP \;\; NP$
$NP \rightarrow NP \;\; PP$
$VP \rightarrow V$
$VP \rightarrow VP \;\; PP$
$VP \rightarrow VP \;\; NP$
$PP \rightarrow Prep \;\; NP$

$N \rightarrow$ book
$V \rightarrow$ book
$Det \rightarrow$ the
$N \rightarrow$ flight
$Prep \rightarrow$ through
$N \rightarrow$ Houston

CFG

CFG

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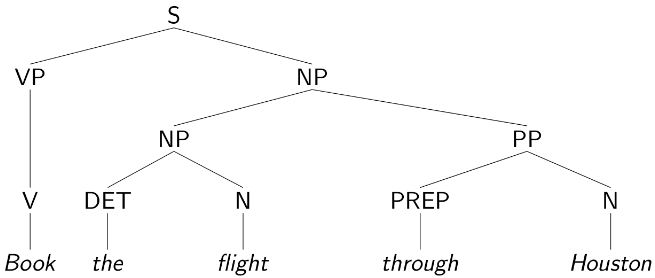

Outline

Parsing

- Taking a string and a grammar and returning proper parse tree(s) for that string
- Covering all and only the elements of the input string
- Reaching the start symbol at the top of the string
- The system cannot select the correct tree among all the possible trees

Main Grammar Fragments

- Sentence
- Noun Phrase
  - Agreement
- Verb Phrase
  - Sub-categorization

Grammar Fragments: Sentence

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- Declaratives
  A plane left.
  $S \rightarrow NP \;\; VP$
- Imperatives
  Leave!
  $S \rightarrow VP$
- Yes-No Questions
  Did the plane leave?
  $S \rightarrow Aux \;\; NP \;\; VP$
- WH Questions
  When did the plane leave?
  $S \rightarrow NP_{WH} \;\; Aux \;\; NP \;\; VP$

Grammar Fragments: NP

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- Each NP has a central critical noun called head
- The head of an NP can be expressed using
  - Pre-nominals: the words that can come before the head
  - Post-nominals: the words that can come after the head

Grammar Fragments: NP

- Pre-nominals
  - Simple lexical items: *the, this, a, an, ...*
    a car
  - Simple possessives
    John's car
  - Complex recursive possessives
    John's sister's friend's car
  - Quantifiers, cardinals, ordinals...
    three cars
  - Adjectives
    large cars

Grammar Fragments: NP

- Post-nominals
  - Prepositional phrases
    flight from Seattle
  - Non-finite clauses
    flight arriving before noon
  - Relative clauses
    flight that serves breakfast

Agreement

- Having constraints that hold among various constituents
- Considering these constraints in a rule or set of rules

  Example: determiners and the head nouns in NPs have to agree in number

  This flight ✔
  Those flights ✔
  This flights ✗
  Those flight ✗

- Grammars that do not consider constraints will over-generate
  - Accepting and assigning correct structures to grammatical examples (*this flight*)
  - But also accepting incorrect examples (*these flight*)

Agreement at sentence level

- Considering similar constraints at sentence level

Example: subject and verb in sentences have to agree in number and person

John flies ✔
We fly ✔
John fly ✗
We flies ✗

Agreement

- Possible CFG solution

$$S_{sg} \rightarrow NP_{sg} \;\; VP_{sg}$$

$$S_{pl} \rightarrow NP_{pl} \;\; VP_{pl}$$

$$NP_{sg} \rightarrow Det_{sg} \;\; N_{sg}$$

$$NP_{pl} \rightarrow Det_{pl} \;\; N_{pl}$$

$$VP_{sg} \rightarrow V_{sg} \;\; NP_{sg}$$

$$VP_{pl} \rightarrow V_{pl} \;\; NP_{pl}$$

...

- Shortcoming:
  - Introducing many rules in the system

Grammar Fragments: VP

- VPs consist of a head verb along with zero or more constituents called arguments

$VP \rightarrow V$	*disappear*
$VP \rightarrow V \;\; NP$	*prefer a morning flight*
$VP \rightarrow V \;\; PP$	*fly on Thursday*
$VP \rightarrow V \;\; NP \;\; PP$	*leave Boston in the morning*
$VP \rightarrow V \;\; NP \;\; NP$	*give me the flight number*

- Arguments
  - Obligatory: complement
  - Optional: adjunct

Sub-categorization

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- Even though there are many valid VP rules, not all verbs are allowed to participate in all VP rules

  disappear a morning flight ✗

- Solution:
  - Subcategorizing the verbs according to the sets of VP rules that they can participate in
  - This is a modern take on the traditional notion of transitive/intransitive
  - Modern grammars may have 100s or such classes

Sub-categorization

- Example:

Sneeze	*John sneezed*
Find	*Please find [a flight to NY]$_{NP}$*
Give	*Give [me]$_{NP}$[a cheaper fair]$_{NP}$*
Help	*Can you help [me]$_{NP}$[with a flight]$_{PP}$*
Prefer	*I prefer [to leave earlier]$_{TO\text{-}VP}$*
Told	*I was told [United has a flight]$_{S}$*

John sneezed the book ✗
I prefer United has a flight ✗
Give with a flight ✗

Sub-categorization

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- The over-generation problem also exists in VP rules
  - Permitting the presence of strings containing verbs and arguments that do not go together

John sneezed the book
$VP \rightarrow V \;\; NP$

- Solution:
  - Similar to agreement phenomena, we need a way to formally express the constraints

Parsing Algorithms

- Top-Down
  - Starting with the rules that give us an S, since trees should be rooted with an S
  - Working on the way down from S to the words

- Bottom-Up
  - Starting with trees that link up with the words, since trees should cover the input words
  - Working on the way up from words to larger and larger trees

Top-Down vs. Bottom-Up

- Top-Down
  - Only searches for trees that can be answers (i.e. S's)
  - But also suggests trees that are not consistent with any of the words

- Bottom-Up
  - Only forms trees consistent with the words
  - But suggests trees that make no sense globally

Top-Down vs. Bottom-Up

- In both cases, we left out how to keep track of the search space and how to make choices

- Solutions
  - Backtracking
    - Making a choice, if it works out then fine
    - If not, then back up and make a different choice
      $\Rightarrow$ duplicated work
  - Dynamic programming
    - Avoiding repeated work
    - Solving exponential problems in polynomial time
    - Storing ambiguous structures efficiently

Dynamic Programming Methods

- CKY: bottom-up
- Early: top-down

Outline

1. Phrase Structure

2. Syntactic Parsing
   - CKY Algorithm

3. Statistical Parsing

Chomsky Normal Form

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- Each grammar can be represented by a set of binary rules

$$A \rightarrow B\ C$$

$$A \rightarrow w$$

A, B, C are noun-terminals w is a terminal

Chomsky Normal Form

- Converting to Chomsky normal form

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

$$X \rightarrow B\ C$$

$$A \rightarrow X\ D$$

X does not occur anywhere else in the the grammar

Chomsky Normal Form

- Converting to Chomsky normal form

$$A \rightarrow B$$

$$B \rightarrow C\ D$$

$$A \rightarrow C\ D$$

CKY Parsing

$$A \rightarrow B\ C$$

- If there is an A somewhere in the input, then there must be a B followed by a C in the input
- If the A spans from i to j in the input, then there must be a k such that $i < k < j$
  - B spans from i to k
  - C spans from k to j

CKY Parsing

[0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	[1,2]	[1,3]	[1,4]	[1,5]
		[2,3]	[2,4]	[2,5]
			[3,4]	[3,5]
				[4,5]
Book	the	flight	through	Houston

0 1 2 3 4 5

CKY Parsing

N → book$_{[0,1]}$ **V → book**$_{[0,1]}$ [0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	Det → the$_{[1,2]}$ [1,2]	[1,3]	[1,4]	[1,5]
		N → flight$_{[2,3]}$ [2,3]	[2,4]	[2,5]
			Prep → through$_{[3,4]}$ [3,4]	[3,5]
				N → houston$_{[4,5]}$ [4,5]

0 Book 1 the 2 flight 3 through 4 Houston 5

CKY Parsing

N → book$_{[0,1]}$ **V → book**$_{[0,1]}$ **NP → N**$_{[0,1]}$ **VP → V**$_{[0,1]}$ **S → VP**$_{[0,1]}$ [0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	Det → the$_{[1,2]}$ [1,2]	[1,3]	[1,4]	[1,5]
		N → flight$_{[2,3]}$ **NP → N**$_{[2,3]}$ [2,3]	[2,4]	[2,5]
			Prep → through$_{[3,4]}$ [3,4]	[3,5]
				N → houston$_{[4,5]}$ **NP → N**$_{[4,5]}$ [4,5]

0 Book 1 the 2 flight 3 through 4 Houston 5

CKY Parsing

$N \rightarrow book_{[0,1]}$ $V \rightarrow book_{[0,1]}$ $NP \rightarrow N_{[0,1]}$ $VP \rightarrow V_{[0,1]}$ $S \rightarrow VP_{[0,1]}$ [0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	$Det \rightarrow the_{[1,2]}$ [1,2]	$NP \rightarrow Det_{[1,2]}, N_{[2,3]}$ [1,3]	[1,4]	[1,5]
		$N \rightarrow flight_{[2,3]}$ $NP \rightarrow N_{[2,3]}$ [2,3]	[2,4]	[2,5]
			$Prep \rightarrow through_{[3,4]}$ [3,4]	[3,5]
				$N \rightarrow houston_{[4,5]}$ $NP \rightarrow N_{[4,5]}$ [4,5]

0 Book 1 the 2 flight 3 through 4 Houston 5

CKY Parsing

N → book$_{[0,1]}$ V → book$_{[0,1]}$ NP → N$_{[0,1]}$ VP → V$_{[0,1]}$ S → VP$_{[0,1]}$ [0,1]	[0,2]	[0,3]	[0,4]	[0,5]
	Det → the$_{[1,2]}$ [1,2]	NP → Det$_{[1,2]}$, N$_{[2,3]}$ [1,3]	[1,4]	[1,5]
		N → flight$_{[2,3]}$ NP → N$_{[2,3]}$ [2,3]	[2,4]	[2,5]
			Prep → through$_{[3,4]}$ [3,4]	PP → Prep$_{[3,4]}$,NP$_{[4,5]}$ [3,5]
				N → houston$_{[4,5]}$ NP → N$_{[4,5]}$ [4,5]

0 Book 1 the 2 flight 3 through 4 Houston 5

CKY Parsing

N → book$_{[0,1]}$ **V → book**$_{[0,1]}$ **NP → N**$_{[0,1]}$ **VP → V**$_{[0,1]}$ **S → VP**$_{[0,1]}$ [0,1]	[0,2]	**NP → NP**$_{[0,1]}$**, NP**$_{[1,3]}$ **VP → VP**$_{[0,1]}$**, NP**$_{[1,3]}$ **S → VP**$_{[0,3]}$ [0,3]	[0,4]	[0,5]
	Det → the$_{[1,2]}$ [1,2]	**NP → Det**$_{[1,2]}$**, N**$_{[2,3]}$ [1,3]	[1,4]	[1,5]
		N → flight$_{[2,3]}$ **NP → N**$_{[2,3]}$ [2,3]	[2,4]	[2,5]
			Prep → through$_{[3,4]}$ [3,4]	**PP → Prep**$_{[3,4]}$**,NP**$_{[4,5]}$ [3,5]
				N → houston$_{[4,5]}$ **NP → N**$_{[4,5]}$ [4,5]

0 Book 1 the 2 flight 3 through 4 Houston 5

CKY Parsing

N → book$_{[0,1]}$ **V → book**$_{[0,1]}$ **NP → N**$_{[0,1]}$ **VP → V**$_{[0,1]}$ **S → VP**$_{[0,1]}$ [0,1]	[0,2]	**NP → NP**$_{[0,1]}$**, NP**$_{[1,3]}$ **VP → VP**$_{[0,1]}$**, NP**$_{[1,3]}$ **S → VP**$_{[0,3]}$ [0,3]	[0,4]	[0,5]
	Det → the$_{[1,2]}$ [1,2]	**NP → Det**$_{[1,2]}$**, N**$_{[2,3]}$ [1,3]	[1,4]	[1,5]
		N → flight$_{[2,3]}$ **NP → N**$_{[2,3]}$ [2,3]	[2,4]	**NP → NP**$_{[2,3]}$**, PP**$_{[3,5]}$ [2,5]
			Prep → through$_{[3,4]}$ [3,4]	**PP→Prep**$_{[3,4]}$**,NP**$_{[4,5]}$ [3,5]
				N → houston$_{[4,5]}$ **NP → N**$_{[4,5]}$ [4,5]

0 Book 1 the 2 flight 3 through 4 Houston 5

CKY Parsing

N → book$_{[0,1]}$ **V → book**$_{[0,1]}$ **NP → N**$_{[0,1]}$ **VP → V**$_{[0,1]}$ **S → VP**$_{[0,1]}$ [0,1]	[0,2]	**NP → NP**$_{[0,1]}$**, NP**$_{[1,3]}$ **VP → VP**$_{[0,1]}$**, NP**$_{[1,3]}$ **S → VP**$_{[0,3]}$ [0,3]	[0,4]	[0,5]
	Det → the$_{[1,2]}$ [1,2]	**NP → Det**$_{[1,2]}$**, N**$_{[2,3]}$ [1,3]	[1,4]	**NP → NP**$_{[1,3]}$**, PP**$_{[3,5]}$ [1,5]
		N → flight$_{[2,3]}$ **NP → N**$_{[2,3]}$ [2,3]	[2,4]	**NP → NP**$_{[2,3]}$**, PP**$_{[3,5]}$ [2,5]
			Prep → through$_{[3,4]}$ [3,4]	**PP → Prep**$_{[3,4]}$**,NP**$_{[4,5]}$ [3,5]
				N → houston$_{[4,5]}$ **NP → N**$_{[4,5]}$ [4,5]

0 Book 1 the 2 flight 3 through 4 Houston 5

CKY Parsing

N → book$_{[0,1]}$ V → book$_{[0,1]}$ NP → N$_{[0,1]}$ VP → V$_{[0,1]}$ S → VP$_{[0,1]}$ [0,1]	[0,2]	NP → NP$_{[0,1]}$, NP$_{[1,3]}$ VP → VP$_{[0,1]}$, NP$_{[1,3]}$ S → VP$_{[0,3]}$ [0,3]	[0,4]	VP → VP$_{[0,1]}$, NP$_{[1,5]}$ VP' → VP$_{[0,3]}$, PP$_{[3,5]}$ S → VP$_{[0,5]}$ S → VP'$_{[0,5]}$ [0,5]
	Det → the$_{[1,2]}$ [1,2]	NP → Det$_{[1,2]}$, N$_{[2,3]}$ [1,3]	[1,4]	NP → NP$_{[1,3]}$, PP$_{[3,5]}$ [1,5]
		N → flight$_{[2,3]}$ NP → N$_{[2,3]}$ [2,3]	[2,4]	NP → NP$_{[2,3]}$, PP$_{[3,5]}$ [2,5]
			Prep → through$_{[3,4]}$ [3,4]	PP → Prep$_{[3,4]}$,NP$_{[4,5]}$ [3,5]
				N → houston$_{[4,5]}$ NP → N$_{[4,5]}$ [4,5]

ambiguity

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Outline

Probabilistic Context Free Grammar (PCFG)

- Grammar G consists of
  - Terminals (T)
  - Non-terminals (N)
  - Start symbol (S)
  - Rules (R)
  - Probability function (P)
    - $P: \ R \rightarrow [0, 1]$
    - $\forall X \in N, \sum_{X \rightarrow \lambda \in R} P(X \rightarrow \lambda) = 1$

CFG

$S \rightarrow NP \;\; VP$
$S \rightarrow VP$
$NP \rightarrow N$
$NP \rightarrow Det\ N$
$NP \rightarrow NP \;\; NP$
$NP \rightarrow NP \;\; PP$
$VP \rightarrow V$
$VP \rightarrow VP \;\; PP$
$VP \rightarrow VP \;\; NP$
$PP \rightarrow Prep \;\; NP$

$N \rightarrow$ book
$V \rightarrow$ book
$Det \rightarrow$ the
$N \rightarrow$ flight
$Prep \rightarrow$ through
$N \rightarrow$ Houston

PCFG

$S \rightarrow NP\ \ VP$	0.9			
$S \rightarrow VP$	0.1			
$NP \rightarrow N$	0.3		$N \rightarrow$ book	0.5
$NP \rightarrow Det\ N$	0.4		$V \rightarrow$ book	1.0
$NP \rightarrow NP\ \ NP$	0.1		$Det \rightarrow$ the	1.0
$NP \rightarrow NP\ \ PP$	0.2		$N \rightarrow$ flight	0.4
$VP \rightarrow V$	0.1		$Prep \rightarrow$ through	1.0
$VP \rightarrow VP\ \ PP$	0.3		$N \rightarrow$ Houston	0.1
$VP \rightarrow VP\ \ NP$	0.6			
$PP \rightarrow Prep\ \ NP$	1.0			

Treebank

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- A treebank is a corpus in which each sentence has been paired with a parse tree

- These are generally created by
  - Parsing the collection with an automatic parser
  - Correcting each parse by human annotators if required

- Requirement:
  detailed annotation guidelines that provide
  - A POS tagset
  - A grammar
  - Annotation schema
    - Instructions for how to deal with particular grammatical constructions

Penn Treebank

- Penn Treebank is a widely used treebank for English
  - Most well-known section: Wall Street Journal Section
    - 1 M words from 1987-1989

```
(S (NP (NNP John))
   (VP (VPZ flies)
       (PP (IN to)
           (NNP Paris)))
   (. .))
```

Statistical Parsing

- Considering the corresponding probabilities while parsing a sentence
- Selecting the parse tree which has the highest probability

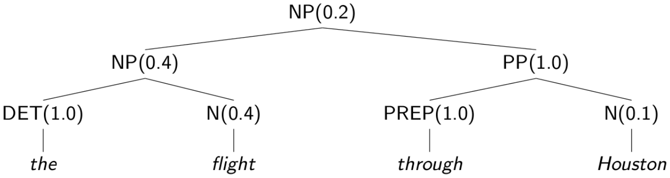
- Tree and string probabilities
  - $P(t)$: the probability of a tree t
    - Product of the probabilities of the rules used to generate the tree
  - $P(s)$: the probability of a string s
    - Sum of the probabilities of the trees which created to parse the string

PCFG

$S \rightarrow NP \;\; VP$	0.9
$S \rightarrow VP$	0.1
$NP \rightarrow N$	0.3
$NP \rightarrow Det\ N$	0.4
$NP \rightarrow NP \;\; NP$	0.1
$NP \rightarrow NP \;\; PP$	0.2
$VP \rightarrow V$	0.1
$VP \rightarrow VP \;\; PP$	0.3
$VP \rightarrow VP \;\; NP$	0.6
$PP \rightarrow Prep \;\; NP$	1.0

$N \rightarrow$ book	0.5
$V \rightarrow$ book	1.0
$Det \rightarrow$ the	1.0
$N \rightarrow$ flight	0.4
$Prep \rightarrow$ through	1.0
$N \rightarrow$ Houston	0.1

Statistical Parsing



$$P(t) = 0.2 \times 0.4 \times 1.0 \times 1.0 \times 0.4 \times 1.0 \times 0.1 = 0.0032$$

Probabilistic CKY Parsing

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0.5 **N → book**$_{[0,1]}$ 1.0 **V → book**$_{[0,1]}$ 0.3*0.5=0.15 **NP → N**$_{[0,1]}$ 0.1*1.0=0.1 **VP → V**$_{[0,1]}$ 0.1*0.1=0.01 **S → VP**$_{[0,1]}$ [0,1]	0.1*0.15*0.16=0.0024 0.6*0.1*0.16=0.0096 0.1*0.0096=0.00096 [0,2]	**NP → NP**$_{[0,1]}$**, NP**$_{[1,3]}$ **VP → VP**$_{[0,1]}$**, NP**$_{[1,3]}$ **S → VP**$_{[0,3]}$ [0,3]	[0,4]	**VP → VP**$_{[0,1]}$**, NP**$_{[1,5]}$ **VP' → VP**$_{[0,3]}$**, PP**$_{[3,5]}$ **S → VP**$_{[0,5]}$ **S → VP'**$_{[0,5]}$ [0,5]
	1.0 **Det → the**$_{[1,2]}$ [1,2]	**NP → Det**$_{[1,2]}$**, N**$_{[2,3]}$ 0.4*1.0*0.4=0.16 [1,3]	[1,4]	**NP → NP**$_{[1,3]}$**, PP**$_{[3,5]}$ [1,5]
		0.4 **N → flight**$_{[2,3]}$ 0.3*0.4=0.12 **NP → N**$_{[2,3]}$ [2,3]	[2,4]	**NP → NP**$_{[2,3]}$**, PP**$_{[3,5]}$ [2,5]
			Prep → through$_{[3,4]}$ [3,4]	**PP → Prep**$_{[3,4]}$**,NP**$_{[4,5]}$ [3,5]
				N → houston$_{[4,5]}$ **NP → N**$_{[4,5]}$ [4,5]

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Exercise

- Implement the probabilistic CKY algorithm which works based on the grammar rules R.

Further Reading

- Speech and Language Processing
  - Chapters 12, 13, 14, 15