Context Free Grammars (CFGs), Probabilistic CFGs and Parsing

Slides modified from Raymond Mooney

Arjun Mukherjee†

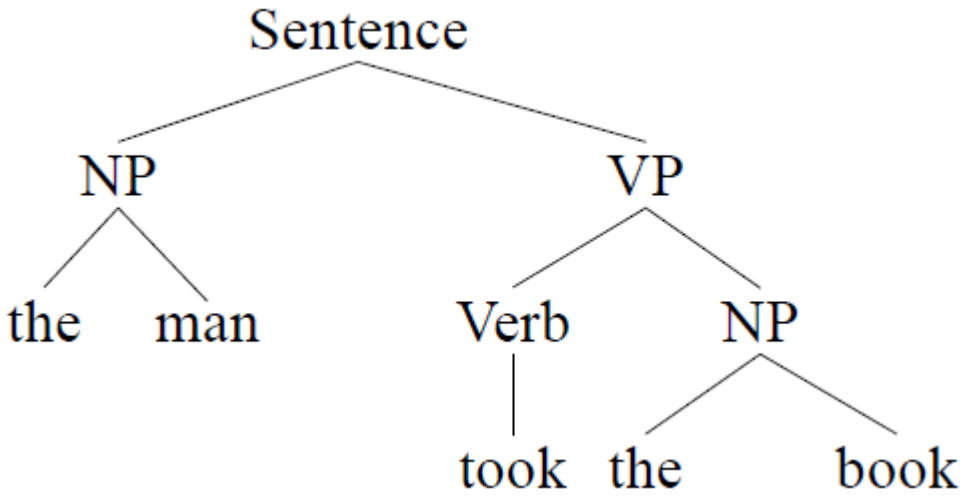
Course webpage: http://www.cs.uh.edu/~arjun/courses/nlp

† Contains contents from [Jurafsky and Martin, 1999] , and various other sources. Referenced in place.

Phrase Chunking

- Chunking: Refers to an analysis of a sentence which identifies the constituents (noun groups, verbs, verb groups, etc.), but does not specify their internal structure, nor their role in the main sentence.

- Hence it is also called “shallow” parsing. A full parse would refer to the internal tree structure and dependencies as follows:



Phrase Chunking

- Noun Phrase (NP): a word or group of words that functions in a sentence as subject, object, or prepositional object.
- Verb phrase (VP): the part of a sentence containing the verb and any direct or indirect object, but not the subject.
- Find all non-recursive noun phrases (NPs) and verb phrases (VPs) in a sentence.
  - [NP I] [VP ate] [NP the spaghetti] [PP with] [NP meatballs].
  - [NP He] [VP reckons] [NP the current account deficit] [VP will narrow] [PP to] [NP only # 1.8 billion] [PP in] [NP September]

Phrase Chunking as Sequence Labeling

- Tag individual words with one of 3 tags
  - B (Begin) word starts new target phrase
  - I (Inside) word is part of target phrase but not the first word
  - O (Other) word is not part of target phrase
- Sample for NP chunking
  - He reckons the current account deficit will narrow to only # 1.8 billion in September.

Begin **Inside** **Other**

Evaluation of Chunking

- Per token accuracy does not evaluate finding correct full chunks. Instead use:

$$\text{Precision} = \frac{\text{Number of correct chunks found}}{\text{Total number of chunks found}}$$

$$\text{Recall} = \frac{\text{Number of correct chunks found}}{\text{Total number of actual chunks}}$$

- Take harmonic mean to produce a single evaluation metric called F measure.

$$F_1 = \frac{1}{(\frac{1}{P} + \frac{1}{R})/2} = \frac{2PR}{P+R}$$

Chunking in Practice

- Stanford Parser
- Try online: http://nlp.stanford.edu:8080/parser/index.jsp
- Sentence: “My dog also likes eating sausage.”
- Chunks upon parse:

Tagging

```
My/PRP$  dog/NN  also/RB  likes/VBZ  eating/VBG  sausage/NN  ./.
```

Parse

```
(ROOT
  (S
    (NP (PRP$ My) (NN dog))
    (ADVP (RB also))
    (VP (VBZ likes)
      (S
        (VP (VBG eating)
          (NP (NN sausage)))))
    (. .)))
```

Chunking in Practice

- OpenNLP
- Opensource NLP toolkit: https://opennlp.apache.org

- Sentence: “Rockwell International Corp.'s Tulsa unit said it signed a tentative agreement extending its contract with Boeing Co. to provide structural parts for Boeing's 747 jetliners.”

- Chunks upon parse:
- Rockwell_NNP International_NNP Corp._NNP 's_POS Tulsa_NNP unit_NN said_VBD it_PRP signed_VBD a_DT tentative_JJ agreement_NN extending_VBG its_PRP$ contract_NN with_IN Boeing_NNP Co._NNP to_TO provide_VB structural_JJ parts_NNS for_IN Boeing_NNP 's_POS 747_CD jetliners_NNS ._.

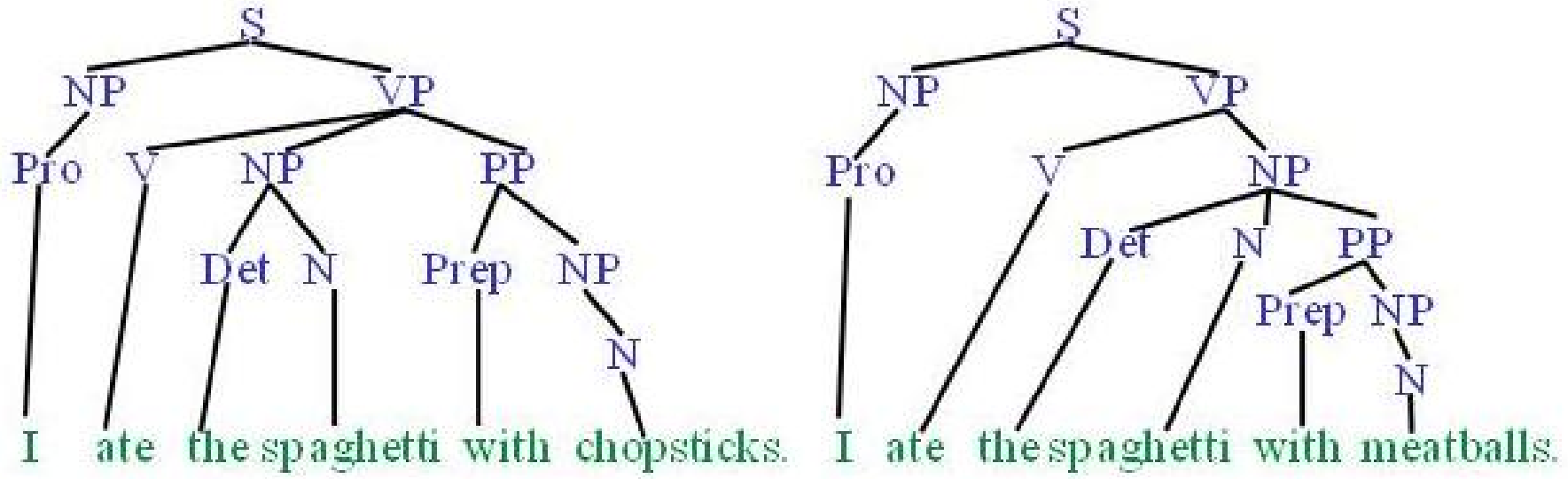
Current Chunking Results

- Best system for NP chunking: F_1=96%
- Typical results for finding range of chunk types (CONLL 2000 shared task: NP, VP, PP, ADV, SBAR, ADJP) is F_1=92−94%

Syntactic Parsing

- (Syntactic) Parsing refers to analysis of natural language according to the rule of a grammar.

- Specifically, emphasis is given on grammatical divisions such as subject and predicate and discovering the dependencies of words using a parse tree.



Context Free Grammar (CFG)

- N a set of ***non-terminal symbols*** (or ***variables***)
- Σ a set of ***terminal symbols*** (disjoint from N)
- R a set of ***productions*** or ***rules*** of the form $A \rightarrow \beta$, where A is a non-terminal and β is a string of symbols from $(\Sigma \cup N)^*$
- S, a designated non-terminal called the ***start symbol***

Simple CFG for ATIS English

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- ATIS: Air Traffic Information System (ATIS) domain
- (Hemphill et al., 1990)

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Lexicon

Det → the | a | that | this
Noun → book | flight | meal | money
Verb → book | include | prefer
Pronoun → I | he | she | me
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Aux → does
Prep → from | to | on | near | through

Sentence Generation

- Sentences are generated by recursively rewriting the start symbol using the productions until only terminals symbols remain.
- Derive the parse tree for: “book the flight through Houston” assuming we know the tree.
- We will see how to discover the parse tree.

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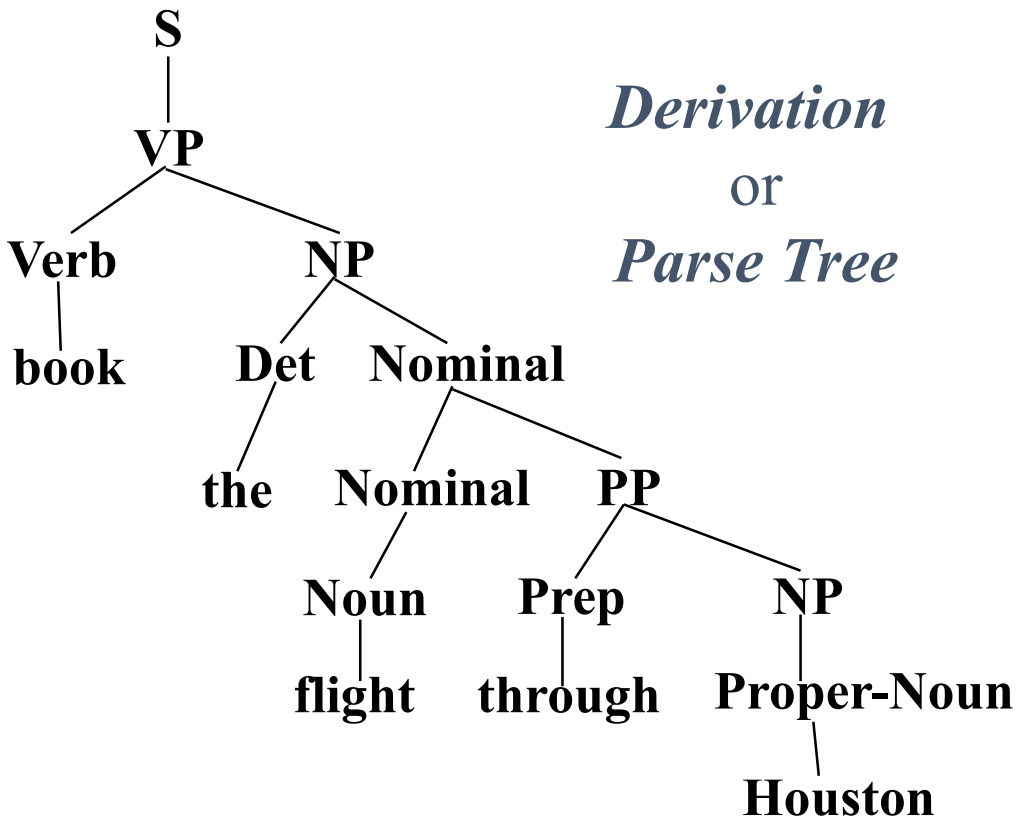

Derivation
or
Parse Tree

Parsing a Sentence using CFG

- **Task:** Given a string of terminals and a CFG, determine if the string can be generated by the CFG.
  - Also return a parse tree for the string
  - Also return all possible parse trees for the string

- **A search problem:** Must search space of derivations for one that derives the given string.
  - **Top-Down Parsing**: Start searching space of derivations for the start symbol.
  - **Bottom-up Parsing**: Start search space of reverse deviations from the terminal symbols in the string.

Parsing Example

- **Q: How do we construct the parse tree for a sentence given a CFG?**

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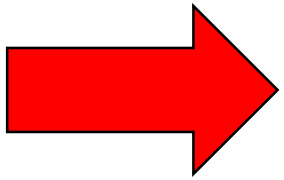
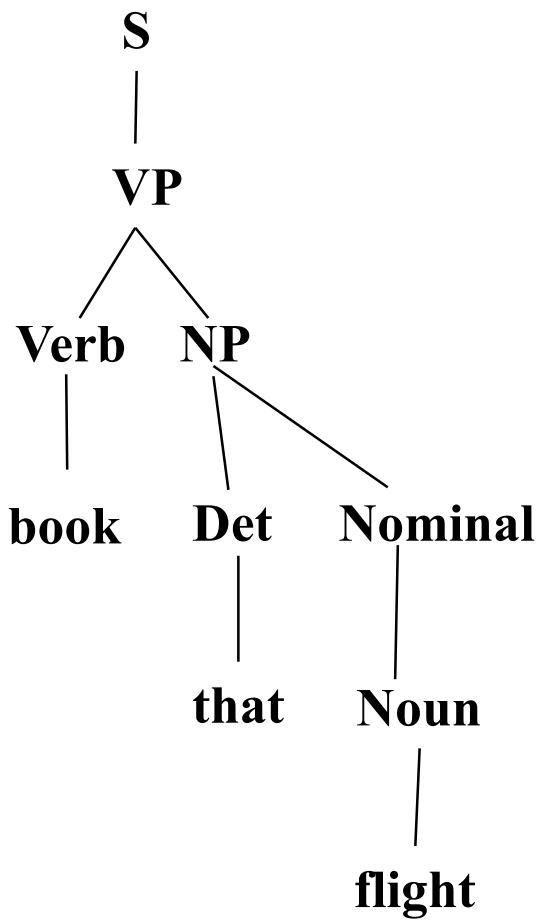
book that flight





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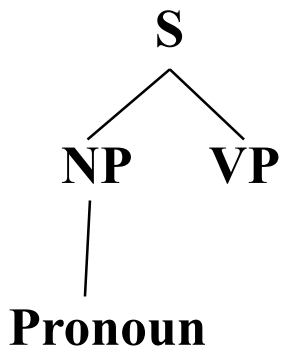

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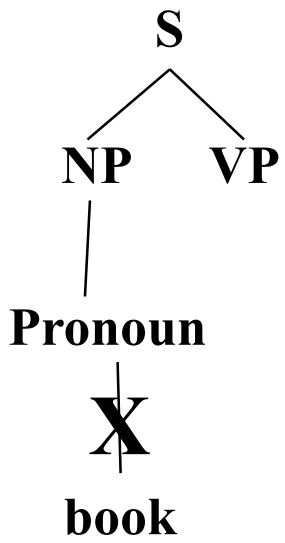

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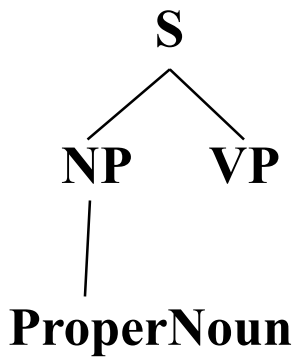

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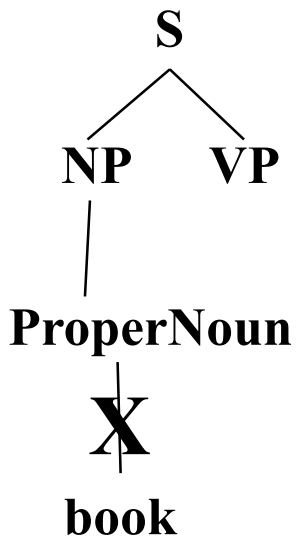

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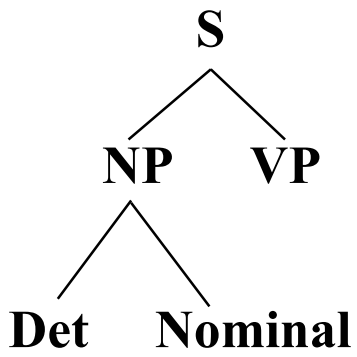

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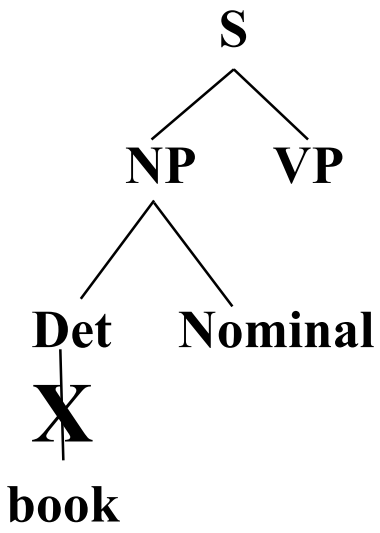

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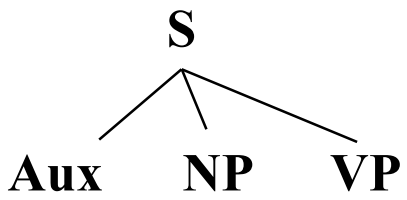

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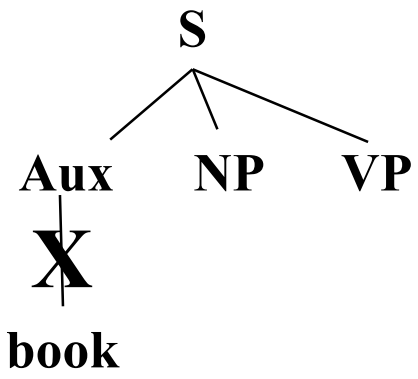

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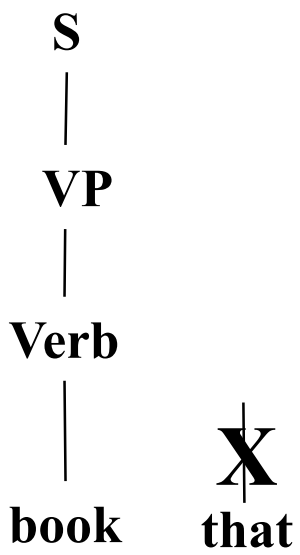

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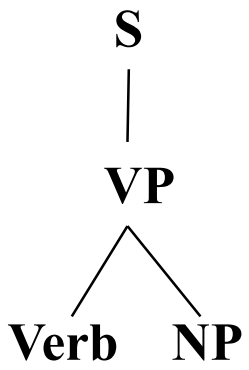

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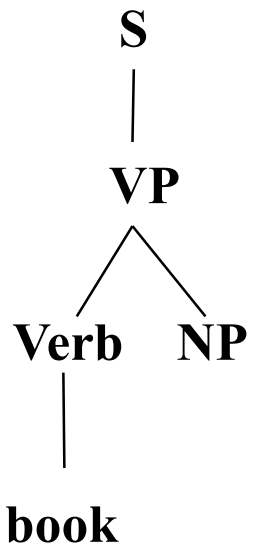

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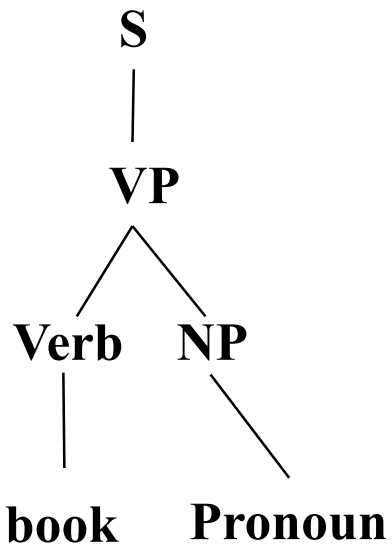

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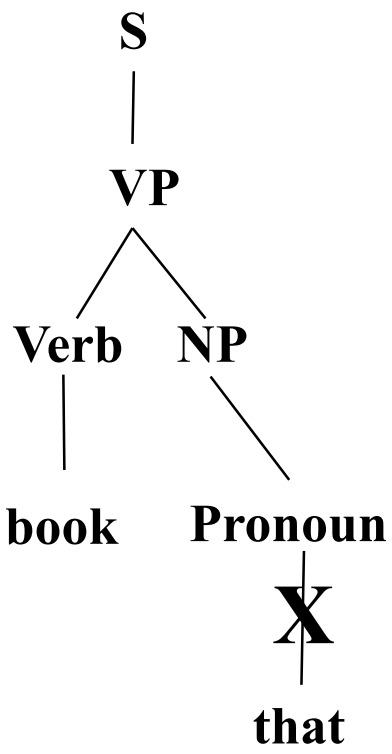

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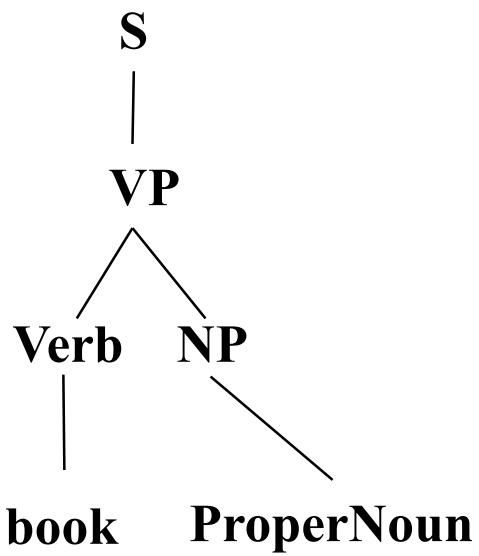

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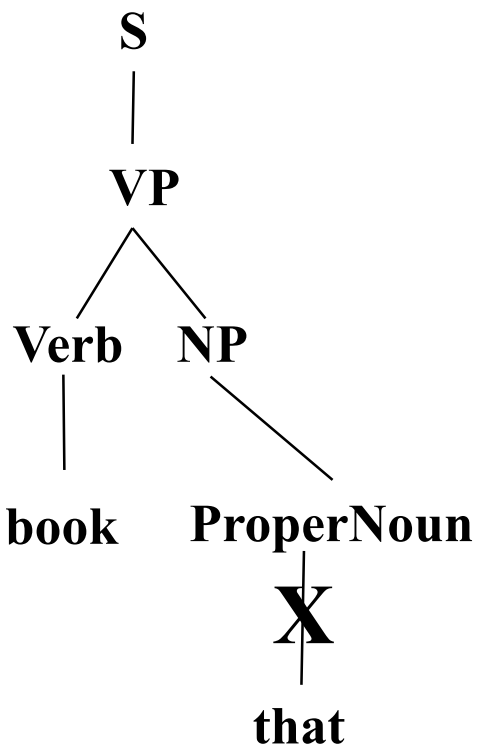

Parsing Example: Top-Down Parsing

Grammar

S → NP VP
S → Aux NP VP
S → VP
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NP → Proper-Noun
NP → Det Nominal
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Lexicon

Det → the | a | that | this
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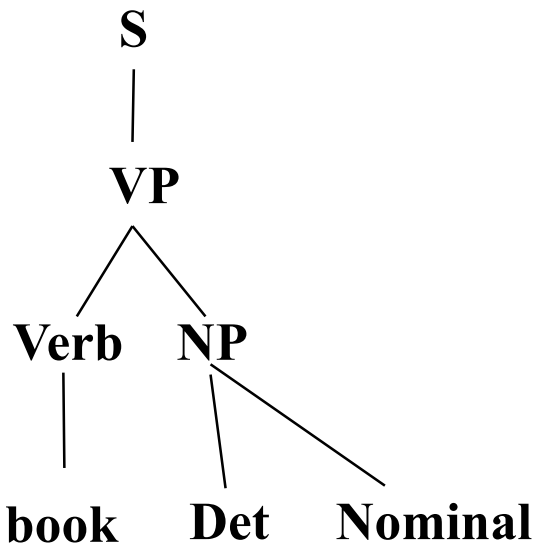

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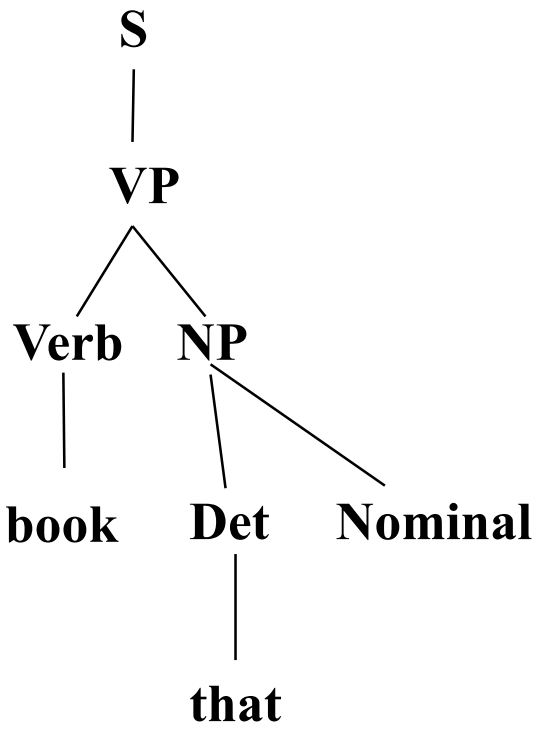

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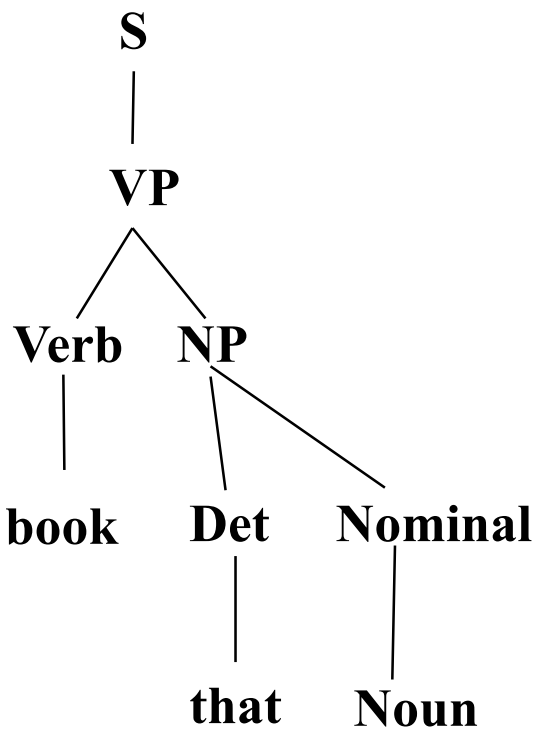

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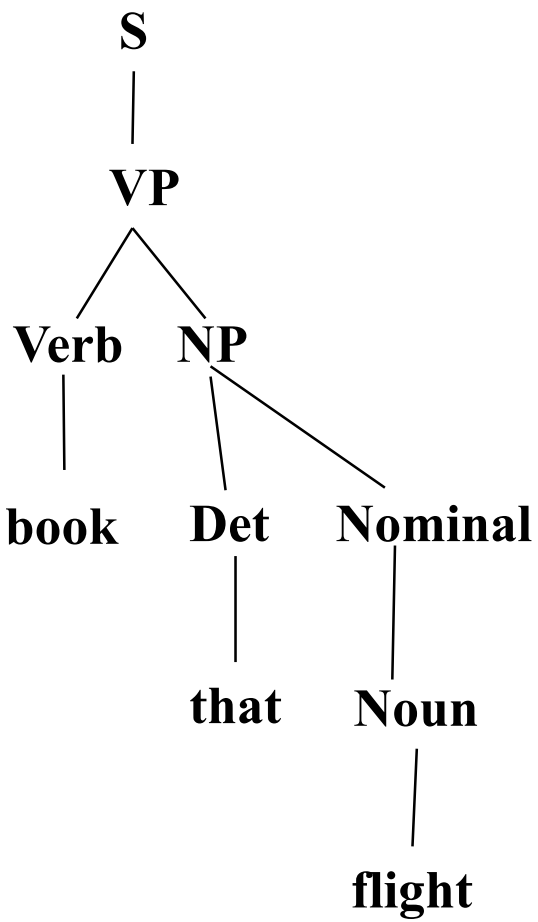

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Generating the sentence: “book that flight”

book that flight

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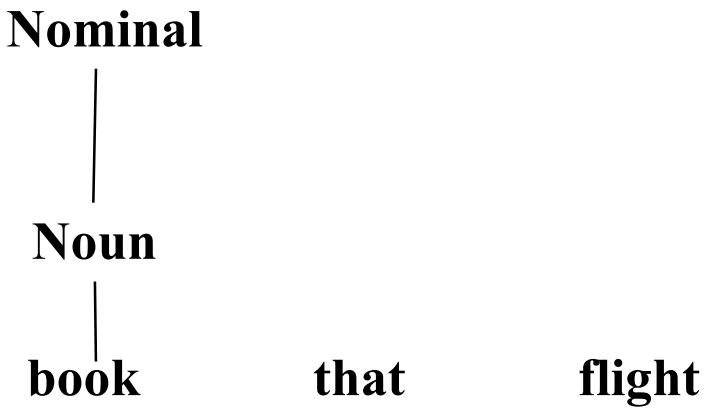

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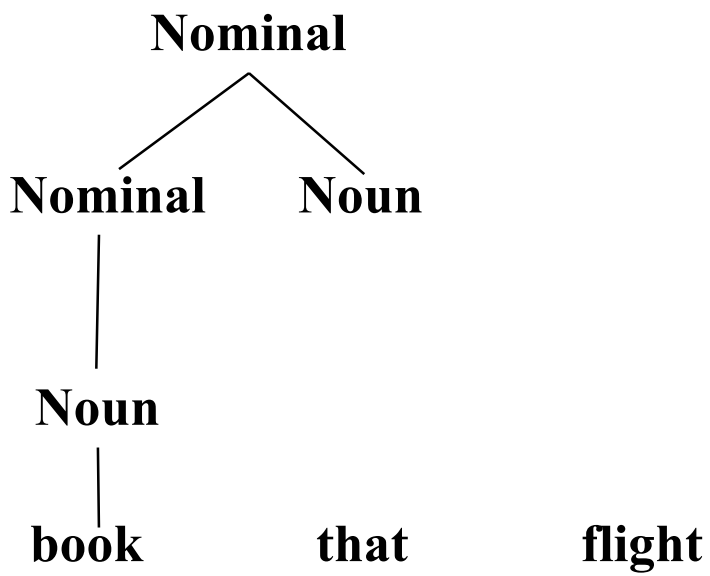

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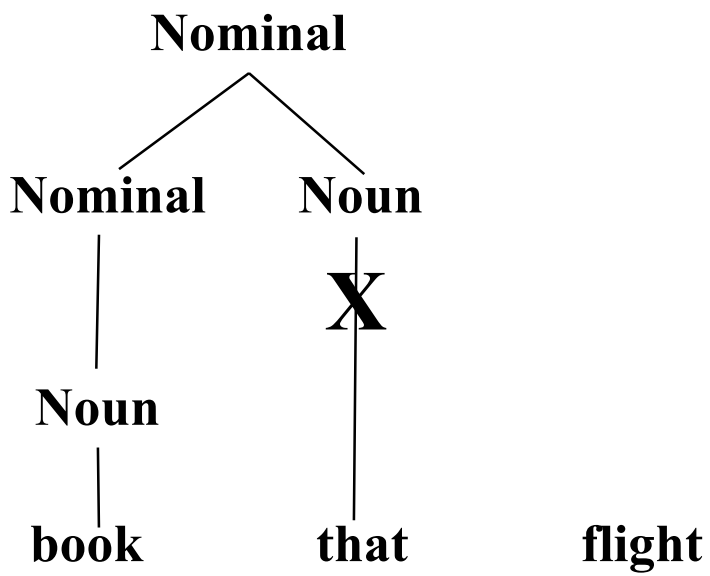

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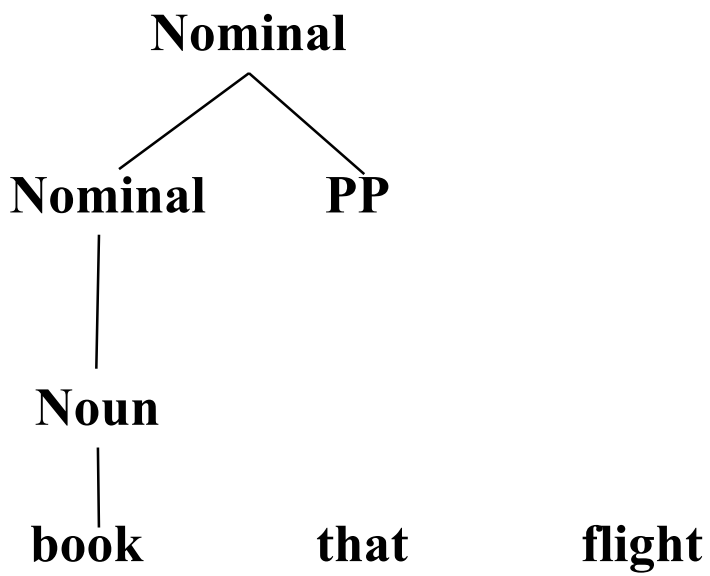

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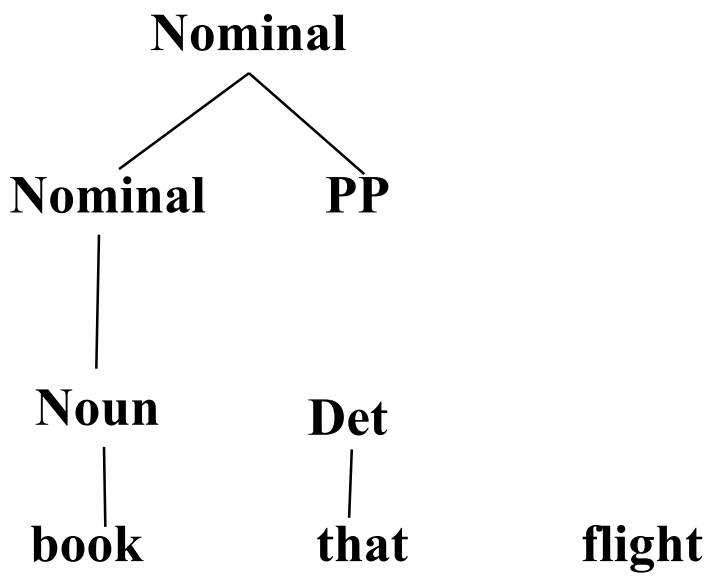

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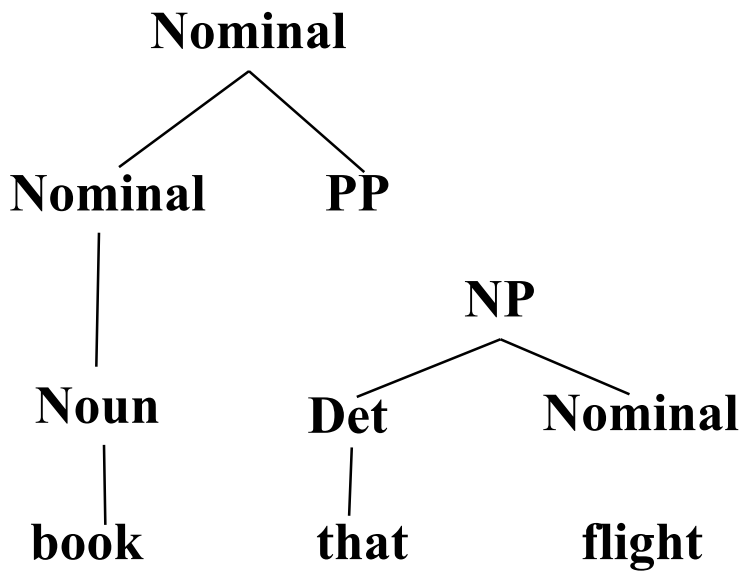

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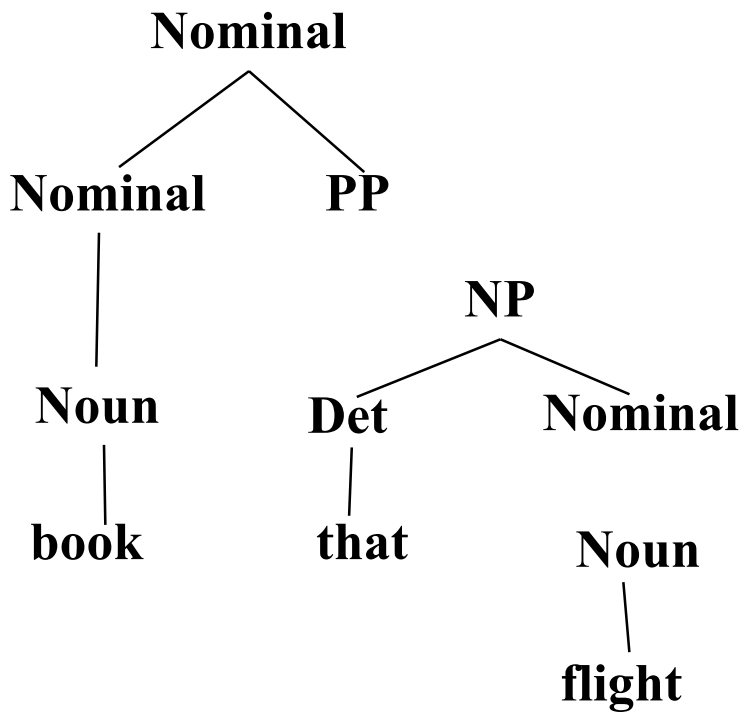

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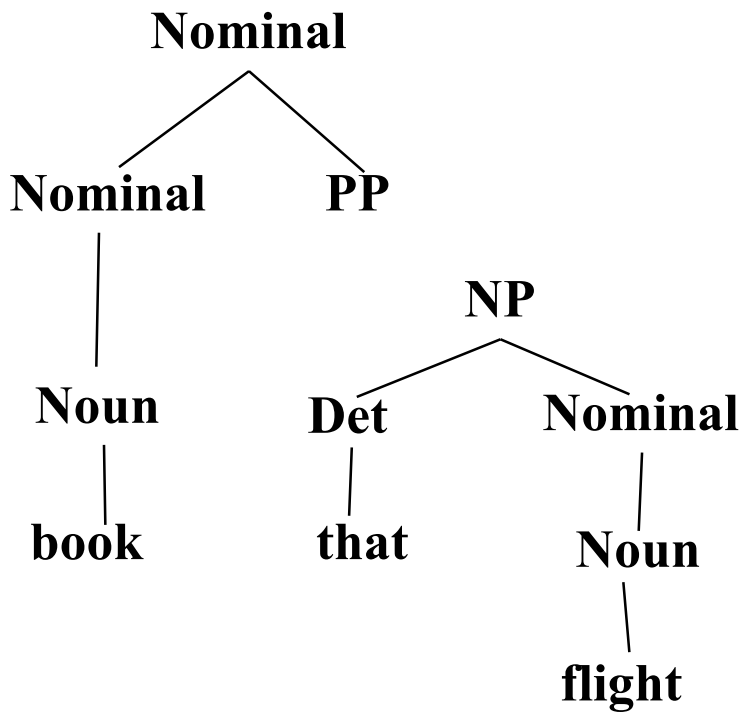

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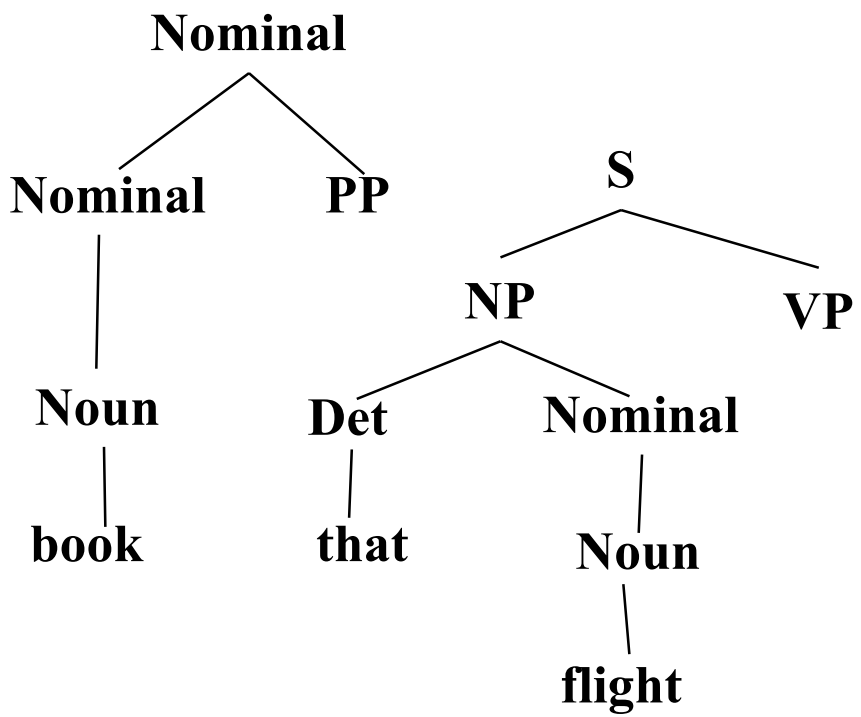

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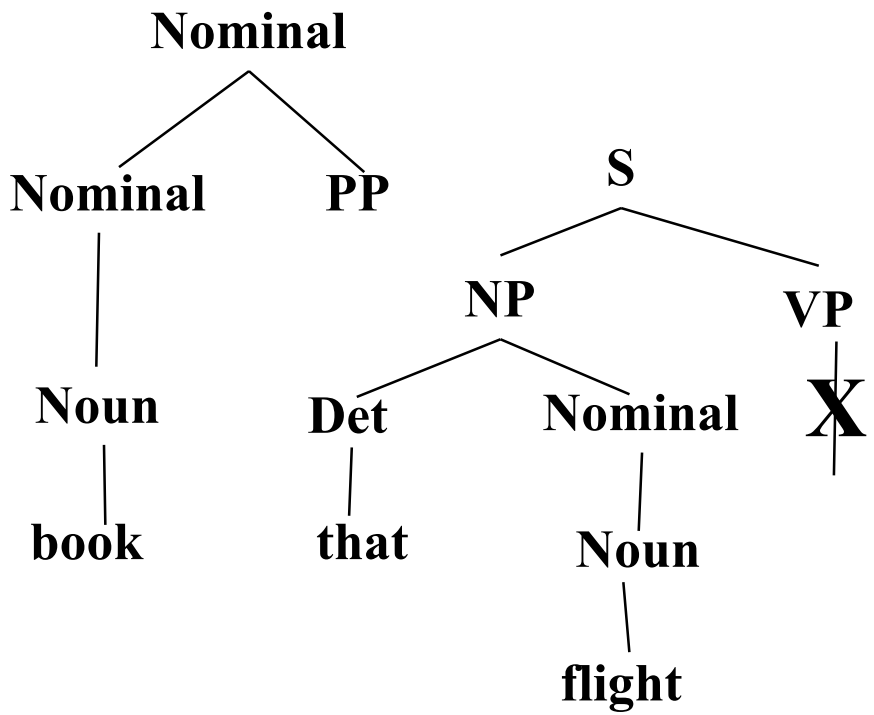

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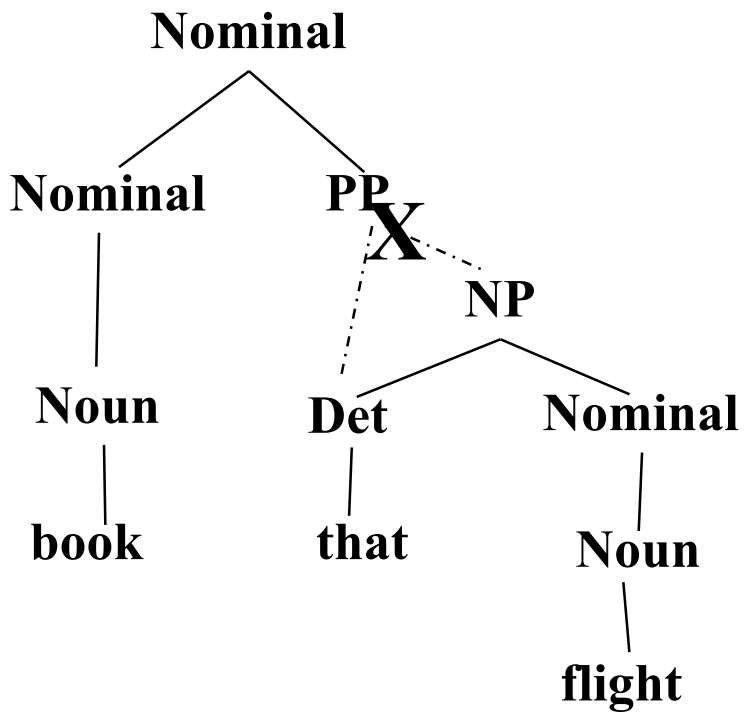

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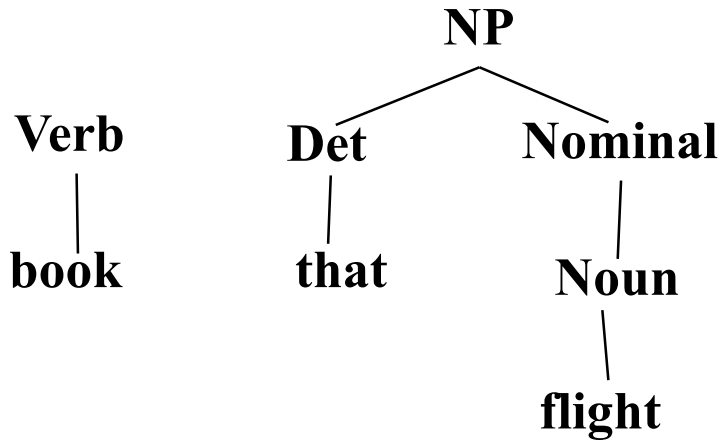

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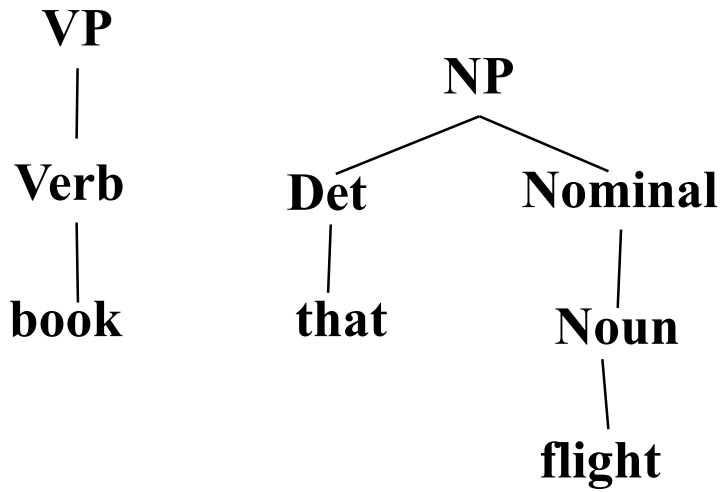

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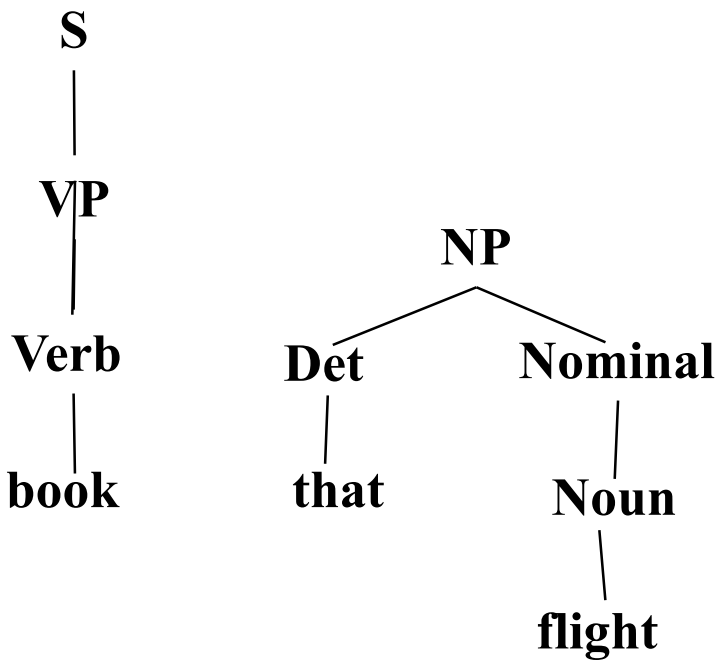

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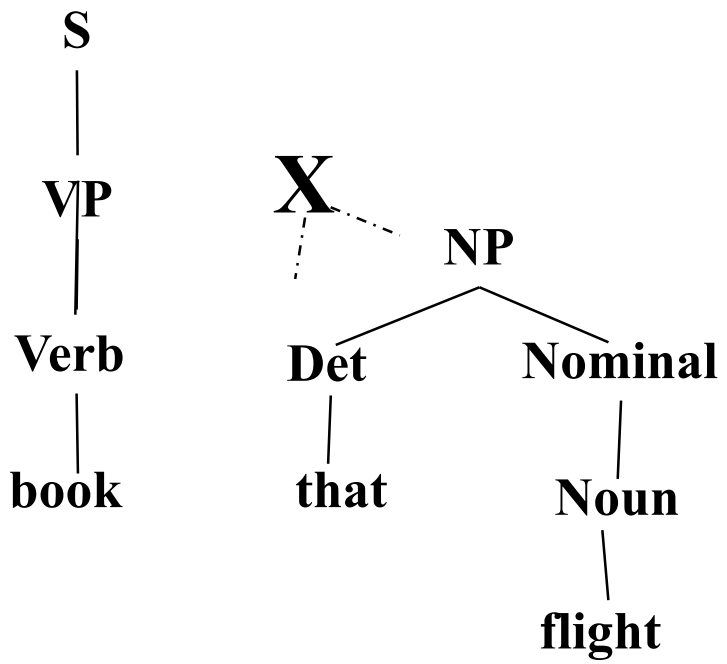

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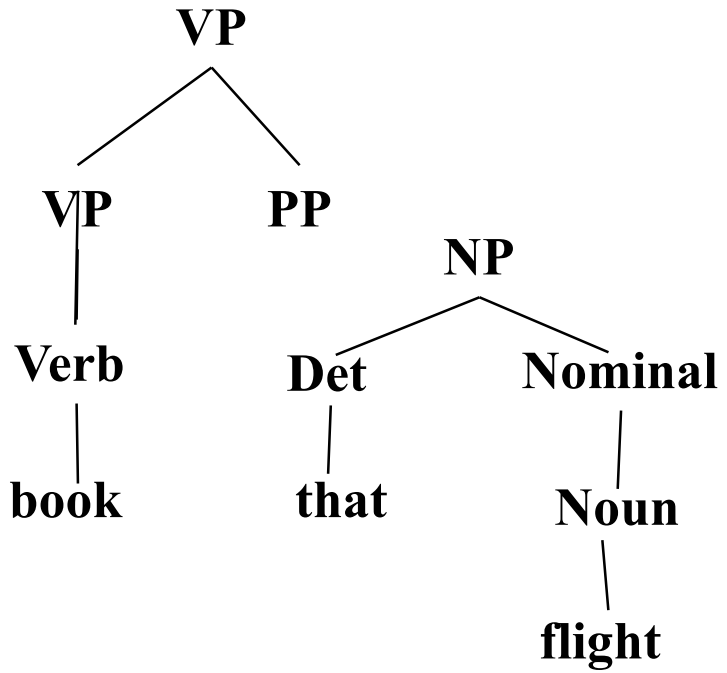

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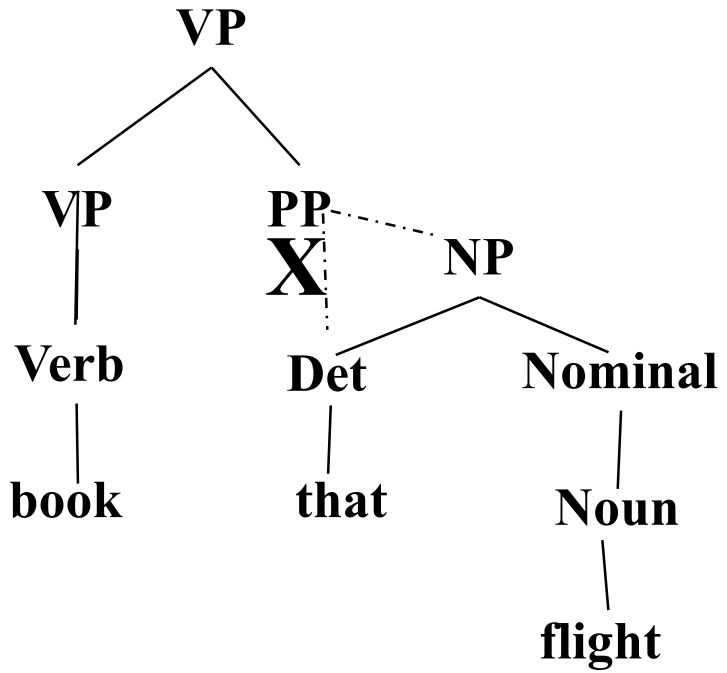

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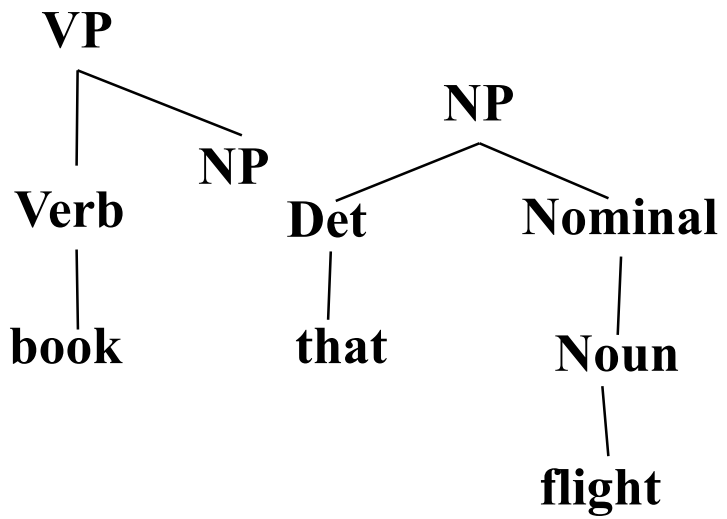

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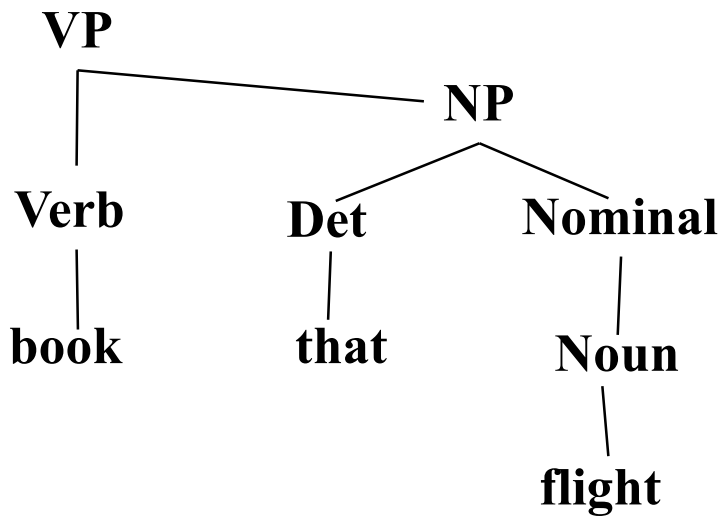

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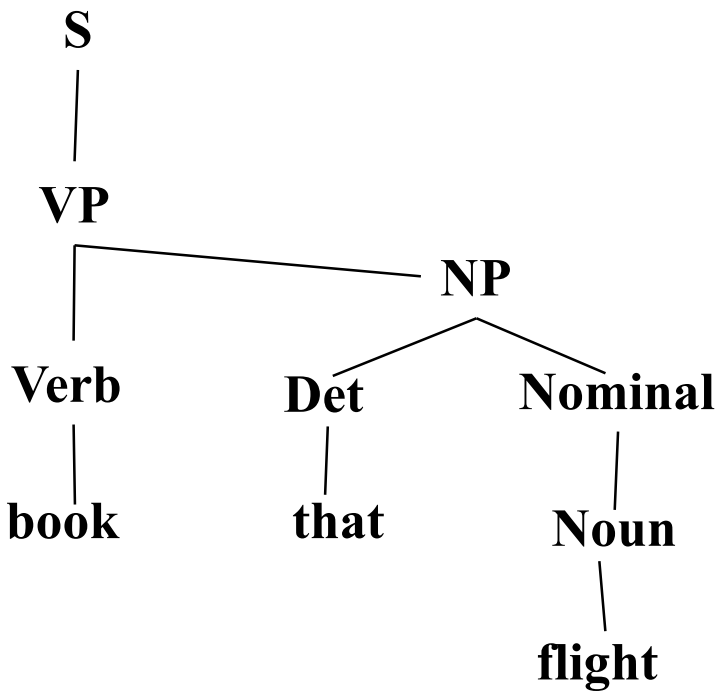
NP → Det Nominal
Nominal → Noun
Nominal → Nominal Noun
Nominal → Nominal PP
VP → Verb
VP → Verb NP
VP → VP PP
PP → Prep NP

Lexicon

Det → the | a | that | this
Noun → book | flight | meal | money
Verb → book | include | prefer
Pronoun → I | he | she | me
Proper-Noun → Houston | NWA
Aux → does
Prep → from | to | on | near | through

Generating the sentence: "book that flight"



Top-Down vs. Bottom-Up Parsing

- Top down never explores options that will not lead to a full parse, but can explore many options that never connect to the actual sentence.
- Bottom up never explores options that do not connect to the actual sentence but can explore options that can never lead to a full parse.
- Relative amounts of wasted search depend on how much the grammar branches in each direction.

Parsing using Dynamic Porgramming

- To avoid extensive repeated work, must cache intermediate results, i.e. completed phrases.
- Caching (memorizing) critical to obtaining a polynomial time parsing (recognition) algorithm for CFGs.
- Dynamic programming algorithms based on both top-down and bottom-up search can achieve $O(n^3)$ recognition time where n is the length of the input string.

Dynamic Programming based Parsers

- **CKY** (Cocke-Kasami-Younger) algorithm based on bottom-up parsing and requires first normalizing the grammar.
- **Earley parser** is based on top-down parsing and does not require normalizing grammar but is more complex.
- More generally, **chart parsers** retain completed phrases in a chart and can combine top-down and bottom-up search.

- **Fortunately…**there are several tools: OpenNLP, Stanford Parser, Lingpipe, etc. which do the job for us ☺

CKY [Cocke-Kasami-Younger]

- First grammar must be converted to **Chomsky normal form (CNF)** in which productions must have either exactly 2 non-terminal symbols on the RHS or 1 terminal symbol (lexicon rules).
- Parse bottom-up storing phrases formed from all substrings in a triangular table (chart).

- Detailed tutorial on CKY parsing algorithm here.

Converting Grammar to CNF

Lexicon

Det → the | a | that | this
Noun → book | flight | meal | money
Verb → book | include | prefer
Pronoun → I | he | she | me
Proper-Noun → Houston | NWA
Aux → does
Prep → from | to | on | near | through

Original Grammar

S → NP VP
S → Aux NP VP

S → VP

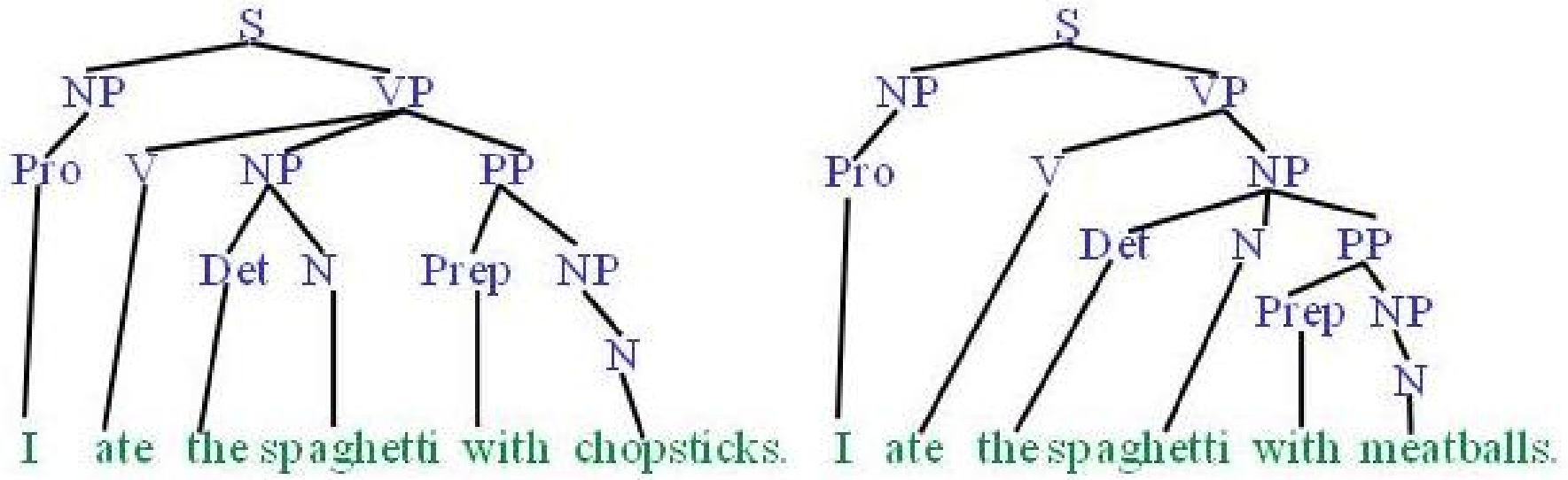
NP → Pronoun
NP → Proper-Noun
NP → Det Nominal
Nominal → Noun
Nominal → Nominal Noun
Nominal → Nominal PP
VP → Verb
VP → Verb NP
VP → VP PP
PP → Prep NP

Chomsky Normal Form (CNF)

S → NP VP
S → X1 VP
X1 → Aux NP
S → book | include | prefer
S → Verb NP
S → VP PP
NP → I | he | she | me
NP → Houston | NWA
NP → Det Nominal
Nominal → book | flight | meal | money
Nominal → Nominal Noun
Nominal → Nominal PP
VP → book | include | prefer
VP → Verb NP
VP → VP PP
PP → Prep NP

Syntactic Ambiguity

- Just produces all possible parse trees.
- Does not address the important issue of ambiguity resolution.
- Q: How to know which parse tree is more probable?



- Addressed using Probabilistic CFG (PCFG)

CFG issues

- Ambiguity (as seen before)
- Addressing some grammatical constraints requires complex CFGs that do no compactly encode the given regularities.
- Some aspects of natural language syntax may not be captured at all by CFGs and require context-sensitivity (productions with more than one symbol on the LHS).

- **BUT (they do have fundamental advantages):**
- CFGs can be used to define the grammar of a natural language.
- Dynamic programming algorithms allow computing a single parse tree in cubic time or all parse trees in exponential time.

Statistical Parsing

- Statistical parsing uses a probabilistic model of syntax in order to assign probabilities to each parse tree.
- Provides principled approach to resolving syntactic ambiguity.
- Allows supervised learning of parsers from tree-banks of parse trees provided by human linguists.
- Also allows unsupervised learning of parsers from unannotated text, but the accuracy of such parsers has been limited.

Probabilistic Context Free Grammar (PCFG)

- A PCFG is a probabilistic version of a CFG where each production has a probability.
- Probabilities of all productions rewriting a given non-terminal must add to 1, defining a distribution for each non-terminal.
- String generation is now probabilistic where production probabilities are used to non-deterministically select a production for rewriting a given non-terminal.

Grammar	Prob	
S → NP VP	0.8	
S → Aux NP VP	0.1	+ 1.0
S → VP	0.1	
NP → Pronoun	0.2	
NP → Proper-Noun	0.2	+ 1.0
NP → Det Nominal	0.6	
Nominal → Noun	0.3	
Nominal → Nominal Noun	0.2	+ 1.0
Nominal → Nominal PP	0.5	
VP → Verb	0.2	
VP → Verb NP	0.5	+ 1.0
VP → VP PP	0.3	
PP → Prep NP	1.0	

A PCFG for ATIS English Corpus

Grammar	Prob	
S → NP VP	0.8	
S → Aux NP VP	0.1	+ 1.0
S → VP	0.1	
NP → Pronoun	0.2	
NP → Proper-Noun	0.2	+ 1.0
NP → Det Nominal	0.6	
Nominal → Noun	0.3	
Nominal → Nominal Noun	0.2	+ 1.0
Nominal → Nominal PP	0.5	
VP → Verb	0.2	
VP → Verb NP	0.5	+ 1.0
VP → VP PP	0.3	
PP → Prep NP	1.0	

Lexicon

Det → the | a | that | this
0.6 0.2 0.1 0.1

Noun → book | flight | meal | money
0.1 0.5 0.2 0.2

Verb → book | include | prefer
0.5 0.2 0.3

Pronoun → I | he | she | me
0.5 0.1 0.1 0.3

Proper-Noun → Houston | NWA
0.8 0.2

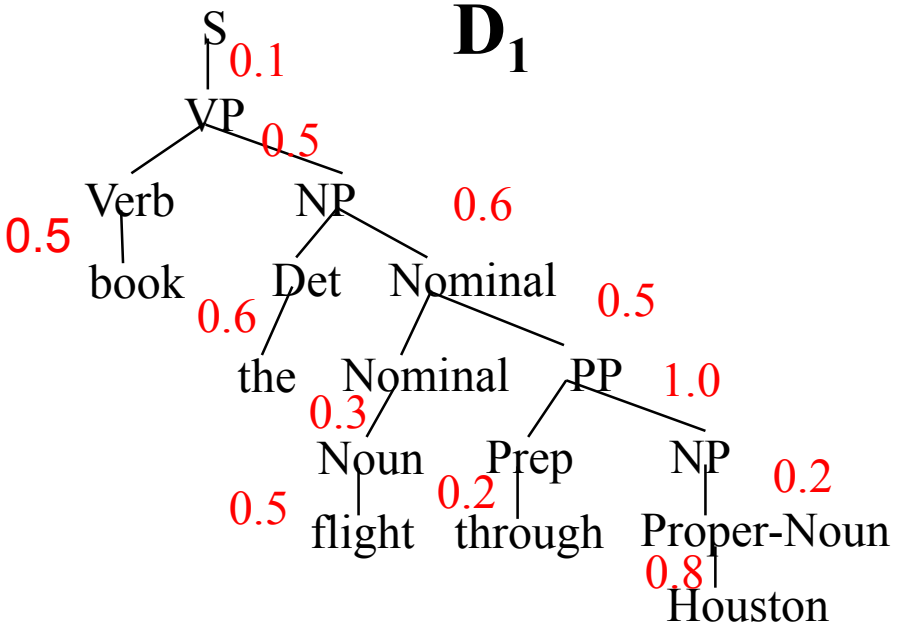
Aux → does
1.0

Prep → from | to | on | near | through
0.25 0.25 0.1 0.2 0.2

Probability of a Sentence

- **Assume productions for each node are chosen independently.**
- **Probability of derivation is the product of the probabilities of its productions.**

$$P(D_1) = 0.1 \times 0.5 \times 0.5 \times 0.6 \times 0.6 \times 0.5 \times 0.3 \times 1.0 \times 0.2 \times 0.2 \times 0.5 \times 0.8 = 0.0000216$$



Grammar	Prob	
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NP → Proper-Noun	0.2	
NP → Det Nominal	0.6	+ 1.0
Nominal → Noun	0.3	
Nominal → Nominal Noun	0.2	
Nominal → Nominal PP	0.5	
VP → Verb	0.2	+ 1.0
VP → Verb NP	0.5	
VP → VP PP	0.3	
PP → Prep NP	1.0	+ 1.0

Lexicon

Det → the | a | that | this
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Noun → book | flight | meal | money
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Proper-Noun → Houston | NWA
0.8 0.2

Aux → does
1.0

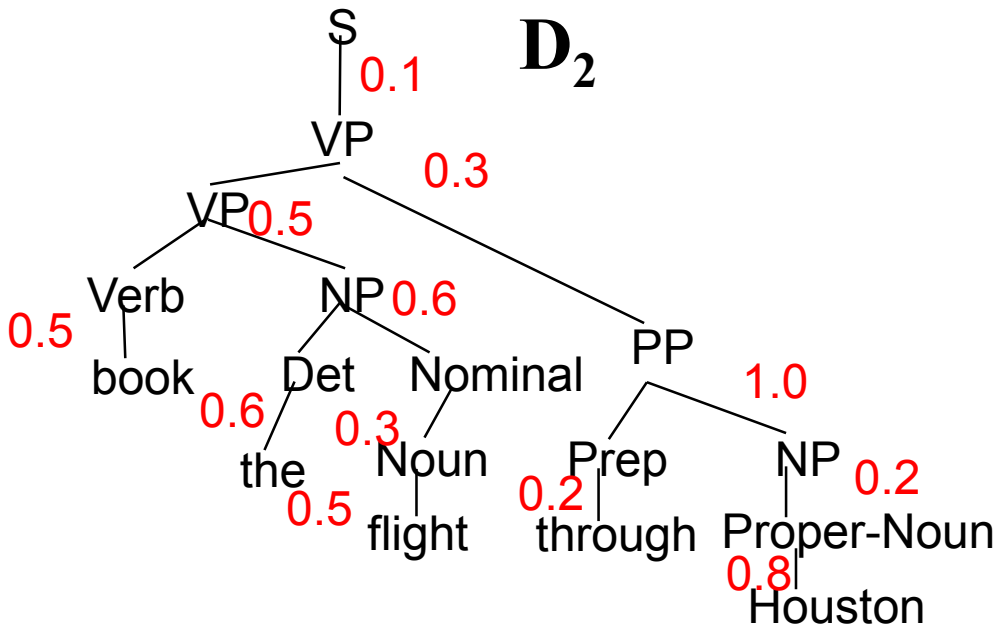
Prep → from | to | on | near | through
0.25 0.25 0.1 0.2 0.2

Syntactic Disambiguation

- Consider another parse tree
- We can resolve ambiguity by picking most probable parse tree
- Since $P(D_1) > P(D_2)$, we can say that the previous parse tree is more probable.
- **Q: What does this mean?**

$P(D_2) = 0.1 \times 0.3 \times 0.5 \times 0.6 \times 0.5 \times 0.6 \times 0.3 \times 1.0 \times 0.5 \times 0.2 \times 0.2 \times 0.8$

$= 0.00001296$



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Syntactic Disambiguation

- Probability of a sentence is the sum of the probabilities of all of its derivations.

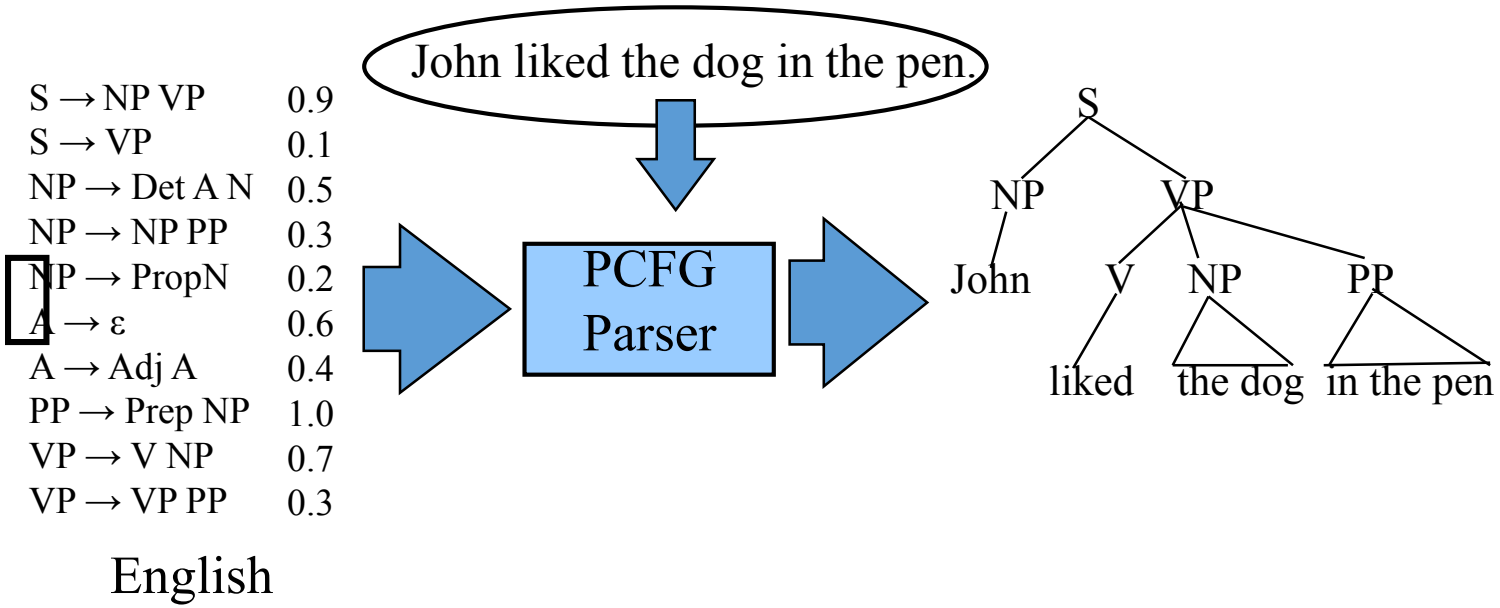
P("book the flight through Houston") =
$P(D_1) + P(D_2) = 0.0000216 + 0.00001296$
$= 0.00003456$

Common PCFG Tasks

- Observation likelihood: To classify and order sentences. (i.e., compute sentence probabilities upon parse tree computation).
- Most likely derivation: To determine the most likely parse tree for a sentence.
- Maximum likelihood training: To train a PCFG to fit empirical training data.

PCFG: Most-Likely Derivation

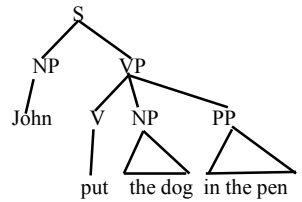
- There is an analog to the Viterbi algorithm to efficiently determine the most probable derivation (parse tree) for a sentence.

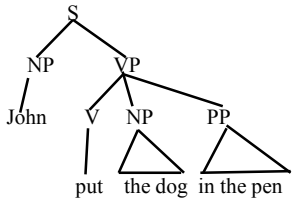


PCFG: Supervised Training

- If parse trees are provided for training sentences, a grammar and its parameters can be can all be estimated directly from counts accumulated from the tree-bank (with appropriate smoothing).

Tree Bank





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•
•

Supervised PCFG Training

S → NP VP	0.9
S → VP	0.1
NP → Det A N	0.5
NP → NP PP	0.3
NP → PropN	0.2
A → ε	0.6
A → Adj A	0.4
PP → Prep NP	1.0
VP → V NP	0.7
VP → VP PP	0.3

English

Estimating Production Probabilities in PCFG Training

- Set of production rules can be taken directly from the set of rewrites in the treebank.
- Parameters can be directly estimated from frequency counts in the treebank.

$$P(\alpha \rightarrow \beta \mid \alpha) = \frac{\text{count}(\alpha \rightarrow \beta)}{\sum_{\gamma} \text{count}(\alpha \rightarrow \gamma)} = \frac{\text{count}(\alpha \rightarrow \beta)}{\text{count}(\alpha)}$$