Natural Language Processing CSCI 4152/6509 — Lecture 18 Syntax of Natural Languages

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Time and date: 14:35 – 15:55, 2-Dec-2025
Location: Studley LSC-Psychology P5260

Previous Lecture

- P0 discussion (4): P-18
- Activation functions, softmax function
- Neural language model, RNN
- Stacked and bidirectional RNN
- LSTM, self-attention, transformers

Part IV: Parsing (Syntactic Processing)

- Prolog introduction
  - unification and backtracking
  - variables, lists; examples: factorial, member

Natural Language Syntax

- Syntax — NLP level of processing
  - Syntax = sentence structure; i.e., study of the phrase structure
- *sýntaxis* (Greek) — "setting out together, arrangement"
- Words are not randomly ordered — word order is important and non-trivial
- There are "free-order" languages (e.g., Latin, Russian), but they are not completely order free.
- Reading: Chapter 12 (JM book) or Ch.18 (JM on-line)

Phrase Structure and Dependency Structure

- Two ways of organizing sentence structure:
    - phrase structure
    - dependency structure
- Phrase structure
    - nested consecutive groupings of words
- Dependency structure
    - dependency relations between words
- The main NLP task at the syntax level: *parsing*
    - given a sentence, find the correct structure

Phrase Structure

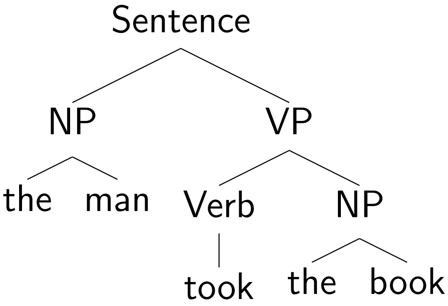
- Phrase Structure Grammars or Context-Free Grammars
- A hierarchical view of sentence structure:
  - words form phrases
  - phrases form clauses
  - clauses form sentences
- Parsing: given a sentence find the context-free parse tree; a.k.a. phrase structure parse tree

Example Sentence

the man took the book

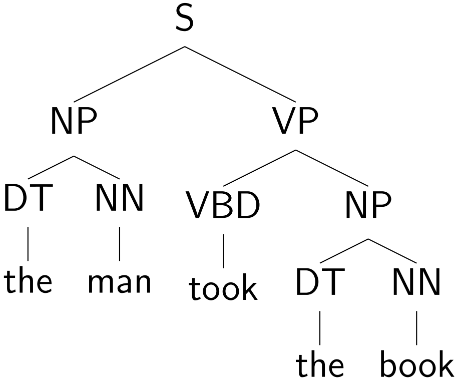
Phrase Structure Parse Tree Examples

- Phrase Structure parse trees are also called Context-Free parse trees
- This example is from the seminal Noam Chomsky's paper in 1956:



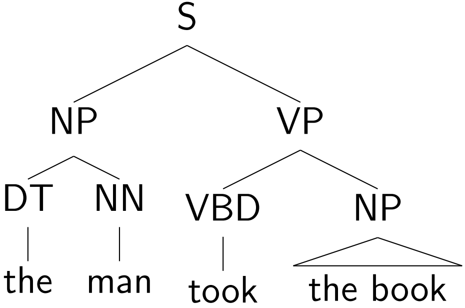
Parse Tree Examples (Penn treebank tagset)

- Using Penn treebank tagset:



Parse Tree Examples (‘triangle’ notation)

- Sometimes we simplify a parse tree by ignoring a part of the structure, as in:

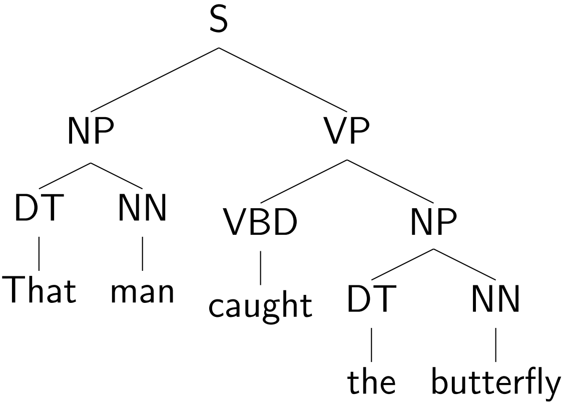


Parse Tree Example 2 (‘butterfly’ sentence)

That man caught the butterfly with a net

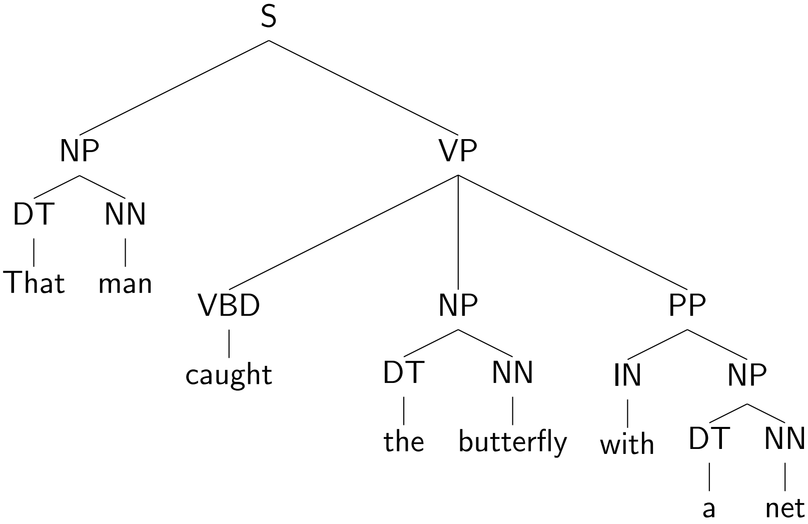
Parse Tree Example 2 (‘butterfly’)

- Another example:



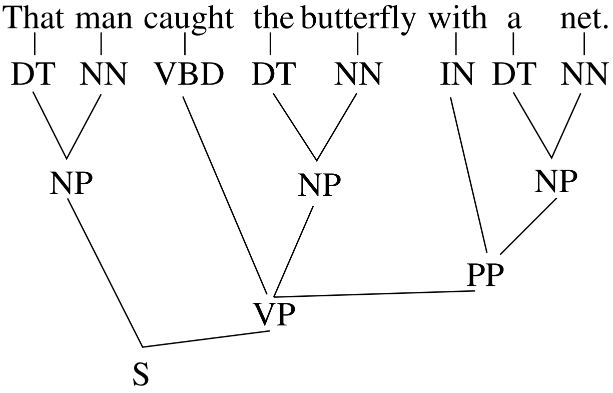
Parse Tree Example3 (‘butterfly’ extended)

- Extending the previous example:



Parse Tree Example (root bottom)

- Representing parse trees in the bottom-up direction:



Some Basic Notions in Context-Free Trees

- Context-free trees, also called phrase structure trees, parse trees, syntactic trees
- Node relations: root, leaf, parent (mother), child (daughter), sibling, ancestor, descendant, dominate
- Context-free grammar
- Consider for example the context-free grammar induced by the last parse tree shown

Context-Free Grammars (CFG) Review

CFG is a tuple (V, T, P, S), where

- V is a finite set of **variables** or **non-terminals**; e.g., $V = \{\mathit{S}, \mathit{NP}, \mathit{DT}, \mathit{NN}, \mathit{VP}, \mathit{VBD}, \mathit{PP}, \mathit{IN}\}$
- T is a finite set of **terminals**, words, or lexemes; e.g., $T = \{$That, man, caught, the, butterfly, with, a, net$\}$
- P is a set of **rules** or **productions** in the form $X \to \alpha$, where $X \in V$ and $\alpha \in (V \cup T)^*$; e.g., $P = \{\mathit{S} \to \mathit{NP}\ \mathit{VP},\ \ \mathit{NP} \to \mathit{DT}\ \mathit{NN},\ \ \mathit{DT} \to \mathrm{That},\ \ \mathit{NP} \to \epsilon\}$
- S is the **start symbol** $S \in V$

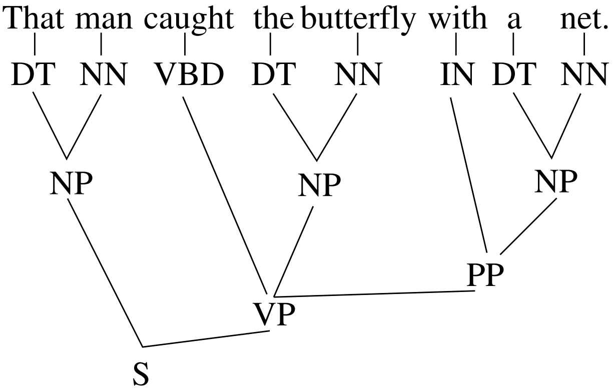
Some Notions about CFGs

- CFG, also known as Phrase-Structure Grammar (PSG)
- Equivalent to BNF (Backus-Naur form)
- Idea from Wundt (1900), formally defined by Chomsky (1956) and Backus (1959)
- Typical notation (V, T, P, S); also (N, Σ, R, S)

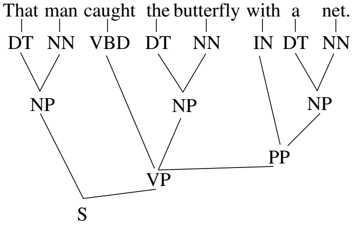
CFG Derivations

- Direct derivation, derivation
- Example of a direct derivation: $S \Rightarrow NP\ VP$
- Example of a derivation (beginning of):
  $S \Rightarrow NP\ VP \Rightarrow DT\ NN\ VP \Rightarrow \text{That}\ NN\ VP \Rightarrow \ldots$
- Left-most and right-most derivation

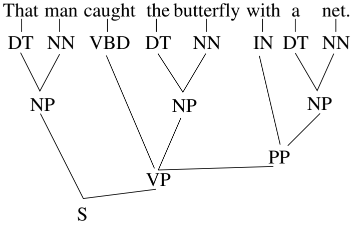
Parse Tree Example (revisited)



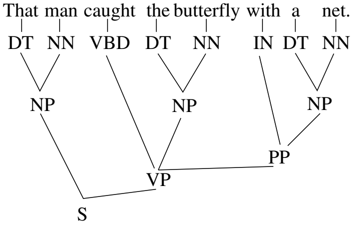
A Derivation Example (random)



Leftmost Derivation Example



Rightmost Derivation Example



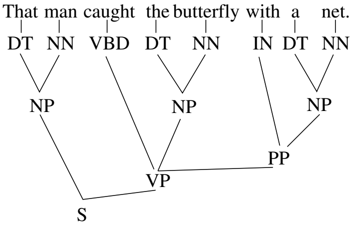
Leftmost Derivation Example

$$
\begin{aligned}
S \;\Rightarrow\;& NP\ VP \Rightarrow DT\ NN\ VP \Rightarrow \text{That}\ NN\ VP \Rightarrow \text{That man}\ VP \\
\Rightarrow\;& \text{That man}\ VBD\ NP\ PP \\
\Rightarrow\;& \text{That man caught}\ NP\ PP \\
\Rightarrow\;& \text{That man caught}\ DT\ NN\ PP \\
\Rightarrow\;& \text{That man caught the}\ NN\ PP \\
\Rightarrow\;& \text{That man caught the butterfly}\ PP \\
\Rightarrow\;& \text{That man caught the butterfly}\ IN\ NP \\
\Rightarrow\;& \text{That man caught the butterfly with}\ NP \\
\Rightarrow\;& \text{That man caught the butterfly with}\ DT\ NN \\
\Rightarrow\;& \text{That man caught the butterfly with a}\ NN \\
\Rightarrow\;& \text{That man caught the butterfly with a net}
\end{aligned}
$$

Some Notions about CFGs (continued)

- Language generated by a CFG
- Context-Free languages
- Parsing task
- Ambiguous sentences
- Ambiguous grammars
- Inherently ambiguous languages

Bracket Representation of a Parse Tree



Bracket Representation of a Parse Tree

```
(S (NP (DT That)
       (NN man))
   (VP (VBD caught)
       (NP (DT the)
           (NN butterfly))
       (PP (IN with)
           (NP (DT a)
               (NN net)
)  )   )   )
```

Some Notes on CFGs

- Left-hand side (lhs) and right-had side (rhs) of a production

$$\underbrace{S}_{lhs} \rightarrow \underbrace{NP\ VP}_{rhs}$$

- Empty rule (epsilon rule, epsilon production): $V \rightarrow \epsilon$
- Unit production: $A \rightarrow B$, where A and B are non-terminals
- Notational variations:
  - use of '|': $P \rightarrow N \mid A\,P$, instead of $P \rightarrow N,\ \ P \rightarrow A\ P$
  - BNF notation: $P ::= N \mid A\,P$
  - use of word 'opt': $NP\ ::=\ DT\ NN\ PP_{opt}$
  - or Kleene star: $NP\ ::=\ DT\ NN\ PP^{*}$

Typical Phrase Structure Rules in English

- We will cover some typical phrase structure rules
- Specific to English but also generalizable to other languages
- **Not** *all rules are covered*, but the general principles should be adopted

Typical Sentence Rules (S)

```
S -> NP VP              Declarative sentences, e.g.:
              I want a flight from Halifax to Chicago.

S -> VP                 Imperative sentences, e.g.:
                        Show the lowest fare.

S -> Aux NP VP          Yes-no questions, e.g.:
                       Do any of these flights have stops?
          Can you give me some information for United?

S -> Wh-NP VP          Wh-subject questions, e.g.:
                       What airlines fly from Halifax?

S -> Wh-NP Aux NP VP   Wh-non-subject questions, e.g.:
                      What flights do you have on Tuesday?
```

Noun Phrase (NP)

- typically: pronouns, proper nouns, or determiner-nominal construction
- some typical rules

```
NP -> PRP                       e.g.: you
NP -> NNP | NNPS                e.g.: Halifax
NP -> PDT? DT JJ* NN PP*
NP -> NN NN                     e.g.: computer science
```

- in the last rule, we use regular expression notation to describe a set of different rules
- example: all the various flights from Halifax to Toronto
- determiners and nominals
- modifiers before head noun and after head noun
- postmodifier phrases `NP -> DT JJ* NN RelC`

Relative Clauses

- RelC — relative clause
- clause (sentence-like phrase) following a noun phrase
- example: gerundive relative clause:
  flights arriving after 5pm
- example: infinitive relative clause:
  flights to arrive tomorrow
- example: restrictive relative clause:
  flight that was canceled yesterday

Verb Phrase (VP)

- organizes arguments around the verb
- typical rules

```
VP -> Verb            intransitive verbs;
                      e.g.: disappear
VP -> Verb NP         transitive verbs:
                      e.g.: prefer a morning flight
VP -> Verb NP NP      ditransitive verbs:
                      e.g.: send me an email
VP -> Verb PP*        sentential complements
VP -> Verb NP PP*
VP -> Verb NP NP PP*
```

- sentential complements, e.g.:
  You said these were two flights that were the cheapest.

Prepositional Phrase (PP)

- Preposition (IN) relates a noun phrase to other word or phrase
- Prepositional Phrase (PP) consists of a preposition and the noun phrase which is an object of that preposition
- There is typically only one rule for the prepositional phrase: `PP -> IN NP`
- examples: from Halifax, before tomorrow, in the city
- PP-attachment ambiguity

Adjective Phrase (ADJP)

- less common
- examples:
  - She is *very sure of herself.*
  - . . . the *least expensive* fare . . .

Adverbial Phrase (ADVP)

- Example:`(S (NP preliminary findings)`
  ```
     (VP were reported
         (ADVP (NP a year) ago)))
  ```
- another example: years ago

About Typical Rules

- Only some typical rules are presented
- For example: We see the cat, and you see a dog.
- The sentence could be described with: `S -> S CC S`
- Relative clauses are labeled in Penn treebank using SBAR ($\bar{S}$) non-terminal; e.g.: `(S (NP (NP Lorillard Inc.)`

```
   ,
   (NP (NP the unit)
       (PP of (NP (ADJP New York-based)
                  Loews Corp.)))
   (SBAR that
         (S (NP *gap*)
            (VP makes (NP Kent cigarettes))))
   ,)
(VP stopped (VP using (NP crocidolite))))
```

Heads and Dependency (heads-up)

- a phrase typically has a central word called *head*, while other words are direct or indirect *dependents*
- a head is also called a *governor*, although sometimes these concepts are considered somewhat different
- phases are usually called by their head; e.g., the head of a noun phrase is a noun