Natural Language Processing
CSCI 4152/6509 — Lecture 18
Deep Learning and NLP; DCG and PCFG

Instructors: Vlado Keselj

Time and date: 16:05 – 17:25, 18-Nov-2024

Location: Carleton Tupper Building Theatre C

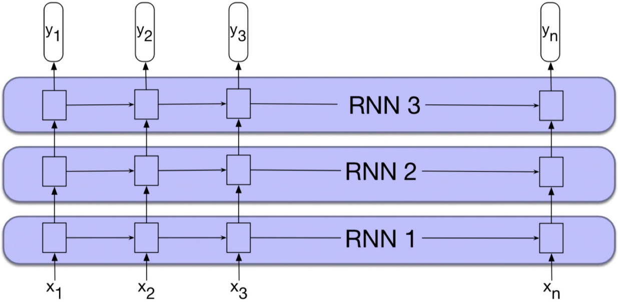
Previous Lecture

Neural networks and deep learning

- Applications
- Some main developments
- Large deep learning models
- Exponential growth in size of LLMs
- Biological neuron, perceptron, feed-forward network
- Activation functions, softmax function
- Neural language model, RNN

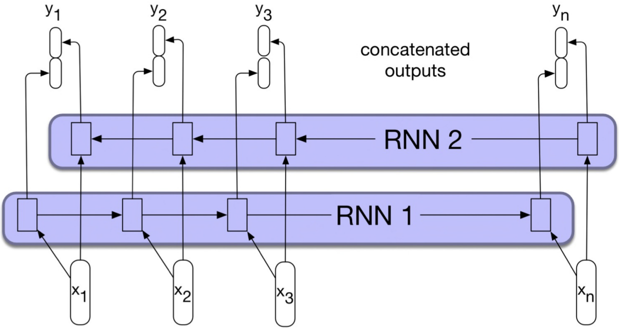
Stacked RNN

- Stacked RNN: Output from lower level is input to higher level; top level is final output (Jurafsky and Martin, Figure 9.10)



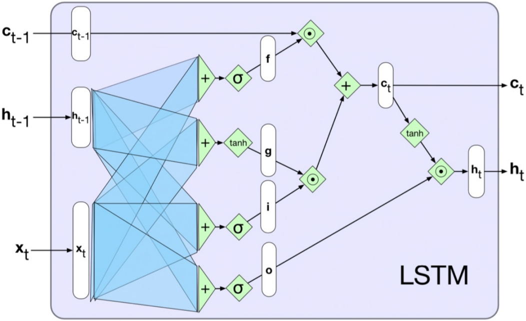
Bidirectional RNN

- Bidirectional RNN; trained forward and backward with concatenated output (Jurafsky and Martin, Figure 9.11)
- Output can be used for sequence labeling, for example



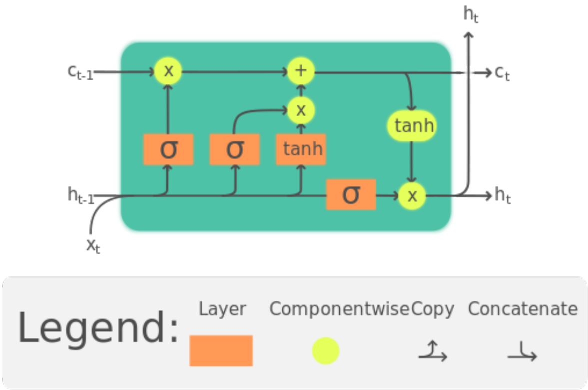
LSTM — Long Short-Term Memory

- LSTM: x_t is input, h_{t-1} is previous hidden state, c_{t-1} is previous long-term context, h_t and c_t is output (Jurafsky and Martin, Figure 9.13)



LSTM Cell

- Another view of LSTM cell (source Wikipedia)

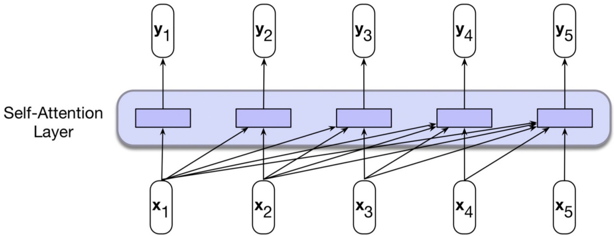


Transformers

- Transformers map a sequence of input vectors to a sequence of output vectors of the same length

$$
\begin{array}{cccc}
x_1 & x_2 & \ldots & x_n \\
\hline
\downarrow & \downarrow & \vdots & \downarrow \\
\hline
y_1 & y_2 & \ldots & y_n
\end{array}
$$

Self-Attention Layer



(Jurafsky and Martin)

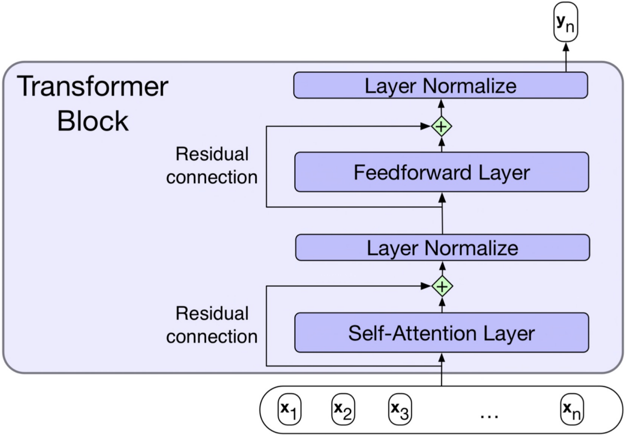
Self-Attention Training

$$\textit{score}(x_i, x_j) = x_i \cdot x_j$$

$$\alpha_{ij} = \text{softmax}(\textit{score}(x_i, x_j)) \quad \forall j \leq i$$

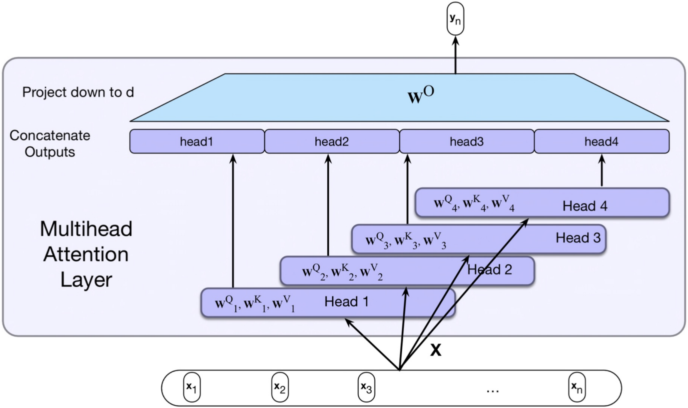
$$y_i = \sum_{j \leq i} \alpha_{ij} x_j$$

Transformer Block



(Jurafsky and Martin)

Multihead Attention Layer



(Jurafsky and Martin)

Encoding Word Positions in Transformers

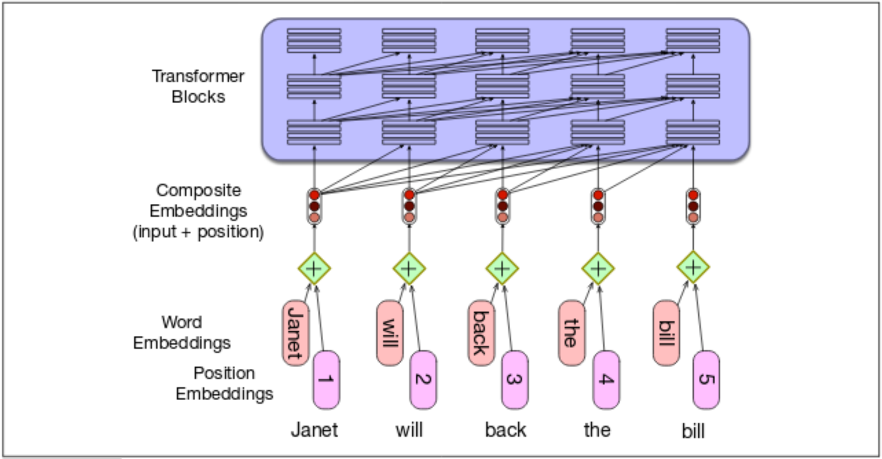


Figure 9.20 A simple way to model position: simply adding an embedding representation of the absolute position to the input word embedding.

from: Jurafsky and Martin, 3rd ed. draft

Training Transformer as a Language Model

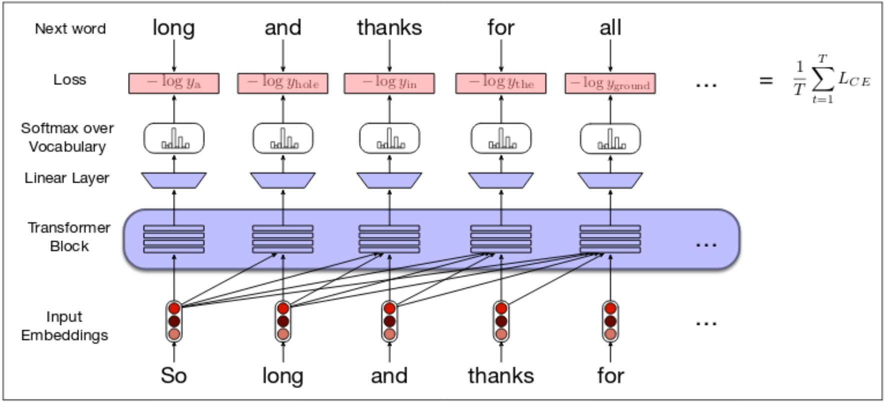


Figure 9.21 Training a transformer as a language model.

from: Jurafsky and Martin, 3rd ed. draft

Text Completion with Transformers

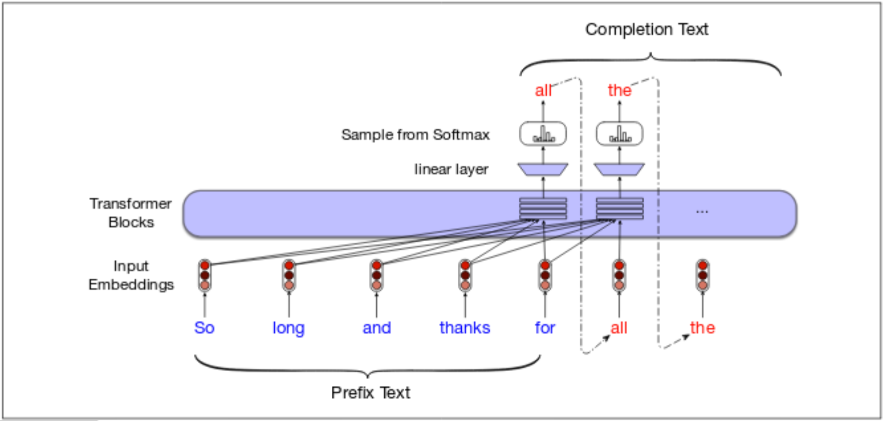


Figure 9.22 Autoregressive text completion with transformers.

from: Jurafsky and Martin, 3rd ed. draft

Parsing Natural Languages

- Must deal with possible ambiguities
- Decide whether to make a phrase structure or dependency parser
- When parsing NLP, there are generally two approaches:
  1. Backtracking to find all parse trees
  2. Chart parsing
- Prolog provides a very expressive way to NL parsing
- FOPL is also used to represent semantics

Parsing with Prolog

- We will go over a brief Prolog review
  - more details are provided in the lab
- Implicative normal form:

$$p_1 \wedge p_2 \wedge \ldots \wedge p_n \Rightarrow q_1 \vee q_2 \vee \ldots \vee q_m$$

- If $m \leq 1$, then the clause is called a **Horn clause.**
- If resolution is applied to two Horn clauses, the result is again a Horn clause.
- Inference with Horn clauses is relatively efficient

Rules

A Horn clause with $m = 1$ is called a **rule**:

$$p_1 \wedge p_2 \wedge \ldots \wedge p_n \Rightarrow q_1$$

It is expressed in Prolog as: `q1 :- p1, p2, ..., p_n.`

Facts

A clause with $m = 0$ is called a **fact**:

$$p_1 \wedge p_2 \wedge \ldots \wedge p_n \Rightarrow \top$$

is expressed in Prolog as: `p1, p2, ..., p_n.`
or `:- p1, p2, ..., p_n.`
and it is called a **fact.**

Rabbit and Franklin Example

The 'rabbit and franklin' example in Prolog:

```
hare(rabbit).
turtle(franklin).
faster(X,Y) :- hare(X), turtle(Y).
```

Save the program in a file, load the file.
After loading the file, on Prolog prompt, type:

```
faster(rabbit,franklin).
```

Try: `faster(X,franklin).` and `faster(X,Y).`

Rabbit and Franklin Example

```
hare(rabbit).
turtle(franklin).
faster(X,Y) :- hare(X), turtle(Y).

?- faster(rabbit,franklin).
```

Rabbit and Franklin Example

```
hare(rabbit).
turtle(franklin).
faster(X,Y) :- hare(X), turtle(Y).

?- faster(X,franklin).
```

Rabbit and Franklin Example

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hare(rabbit).
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faster(X,Y) :- hare(X), turtle(Y).

?- faster(X,Y).
```

Unification and Backtracking

- Two important features of Prolog: unification and backtracking
- Prolog expressions are generally mathematical symbolic expressions, called *terms*
- **Unification** is an operation of making two terms equal by substituting variables with some terms
- **Backtracking:** Prolog uses backtracking to satisfy given goal; i.e., to prove given term expression, by systematically trying different rules and facts, which are given in the program

Example in Unification and Backtracking

- What happens after we type:
  `?- faster(rabbit,franklin).`
- Prolog will search for a 'matching' fact or head of a rule:
  `faster(rabbit,franklin)` and
  `faster(X,Y) :- ...`
- 'Matching' here means **unification**
- After unifying `faster(rabbit,franklin)` and `faster(X,Y)` with substitution `X`←`rabbit` and `Y`←`franklin`, the rule becomes:

```
faster(rabbit,franklin) :-
    hare(rabbit), turtle(franklin).
```

Example (continued)

- Prolog interpreter will now try to satisfy predicates at the right hand side: `hare(rabbit)` and `turtle(franklin)` and it will easily succeed based on the same facts
- If it does not succeed, it can generally try other options through **backtracking**

Variables in Prolog

- Variable names start with uppercase letter or underscore ('_')
- _ is a special, *anonymous variable*
- Examples:
```
?- faster(rabbit,franklin).
Yes ;
...
?- faster(rabbit,X).
X = franklin ;
...
?- hare(X).
X = rabbit ;
```

Lists (Arrays), Structures.

Lists are implemented as linked lists. Structures (records) are expressed as terms. Examples:
In program: `person(john,public,'123-456').`
Interactively: `?- person(john,X,Y).`
`[]` is an empty list.
A list is created as a nested term, usually a special function '.' (dot):

```
?- is_list(.(a, .(b, .(c, [])))).
```

List Notation

`(.(a, .(b, .(c, []))))` is the same as `[a,b,c]`
This is also equivalent to:
`[ a | [ b | [ c | [] ]]]`
or
`[ a, b | [ c ] ]`
A frequent Prolog expression is: `[H|T]`
where H is head of the list, and T is the tail, which is another list.

Example: Calculating Factorial

```
factorial(0,1).
factorial(N,F) :- N>0, M is N-1, factorial(M,FM),
    F is FM*N.
```

After saving in `factorial.prolog` and loading to Prolog:

```
?- ['factorial.prolog'].
% factorial.prolog compiled 0.00 sec, 1,000 bytes

Yes
?- factorial(6,X).

X = 720 ;
```

Example: List Membership

Example (testing membership of a list):

```
member(X, [X|_]).
member(X, [_|L]) :- member(X,L).
```

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.17 (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

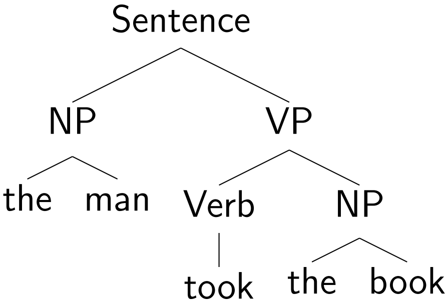
- Phrase Structure Grammars or Context-Free Grammars
- A hierarchical view of sentence structure:
  - words form phrases
  - phrases form clauses
  - clauses form sentences
- Parsing: given a sentence find the context-free parse tree; a.k.a. phrase structure parse tree

Example Sentence

the man took the book

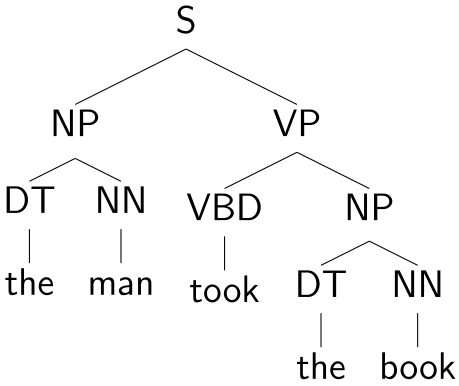
Phrase Structure Parse Tree Examples

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



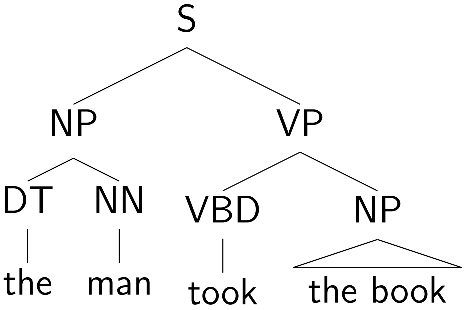
Parse Tree Examples (Penn treebank tagset)

- Using Penn treebank tagset:



Parse Tree Examples ('triangle' notation)

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

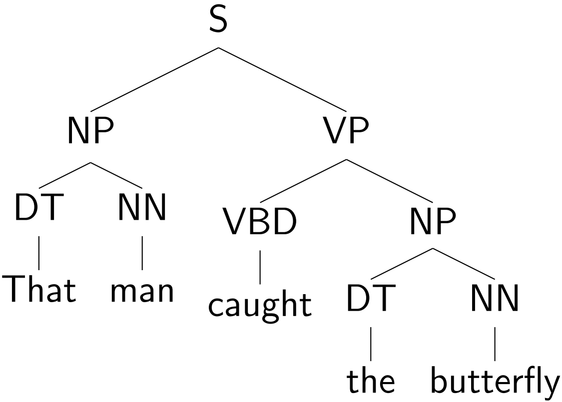


Parse Tree Example 2 (‘butterfly’ sentence)

That man caught the butterfly with a net

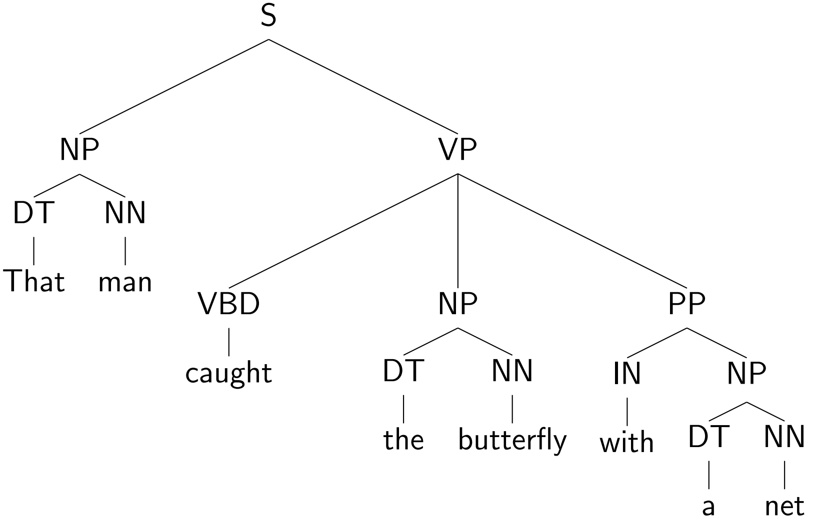
Parse Tree Example 2 (‘butterfly’)

- Another example:



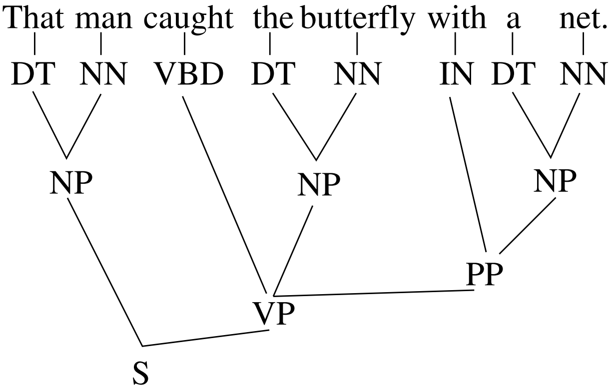
Parse Tree Example3 (‘butterfly’ extended)

- 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 $X \rightarrow \alpha$, where $X \in V$ and $\alpha \in (V \cup T)^*$; e.g., $P = \{\mathit{S} \rightarrow \mathit{NP}\ \mathit{VP},\ \ \mathit{NP} \rightarrow \mathit{DT}\ \mathit{NN},\ \ \mathit{DT} \rightarrow \mathrm{That},\ \ \mathit{NP} \rightarrow \epsilon\}$
- S is the **start symbol** $S \in V$

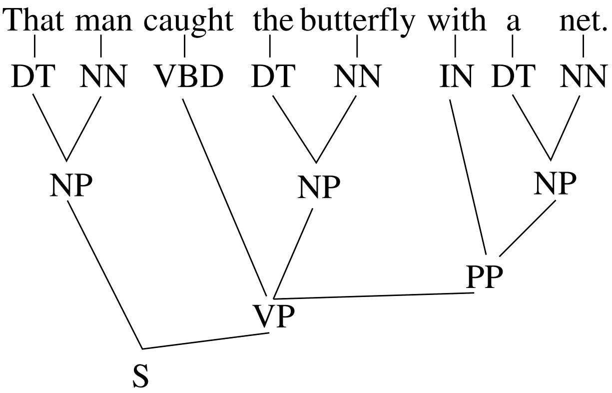
Some Notions about CFGs

- 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)

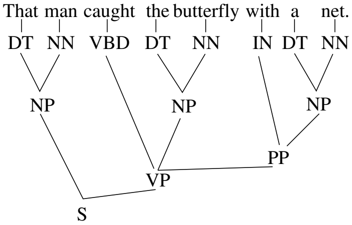
CFG Derivations

- 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

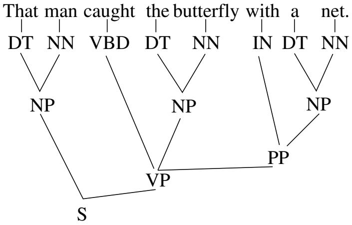
Parse Tree Example (revisited)



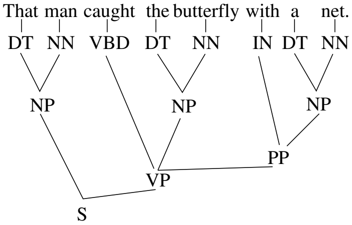
A Derivation Example (random)



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