# Natural Language Processing

## Syntactic parsing

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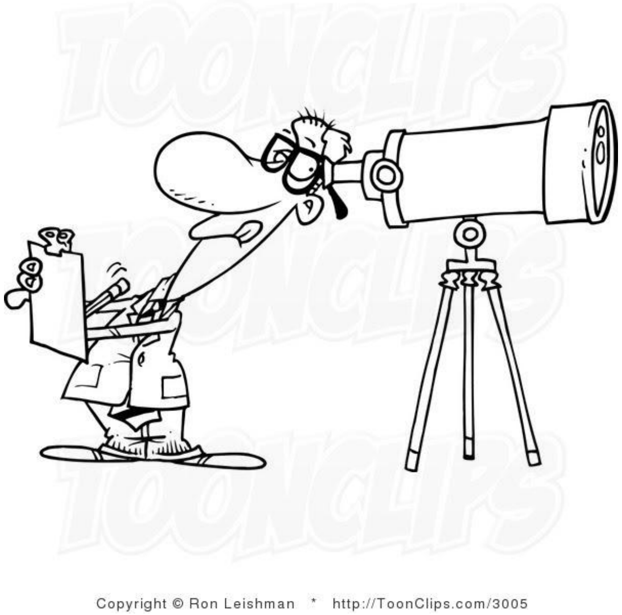
OF COMPUTER SCIENCE & ENGINEERING

# Announcements

- HW2 is due Monday
  - Note that TAs are not required to provide fast responses over weekends
  - Use TAs office hours this week
  - No extensions beyond “standard” late days due to Thanksgiving

# Ambiguity

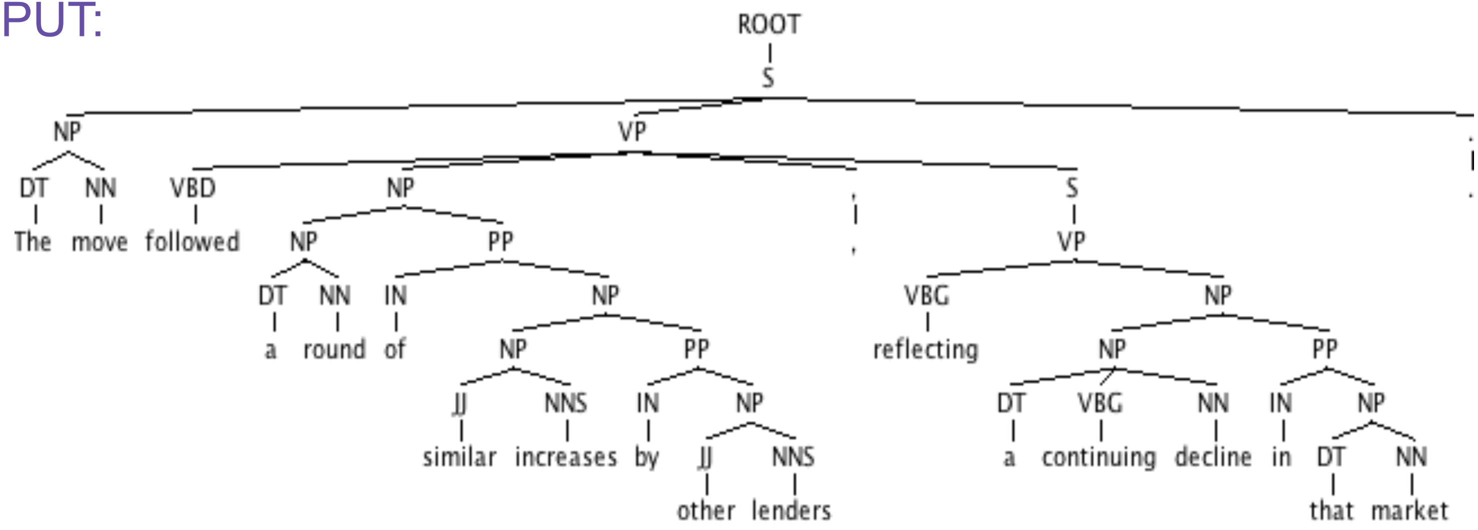
- I saw a girl with a telescope




# Syntactic Parsing

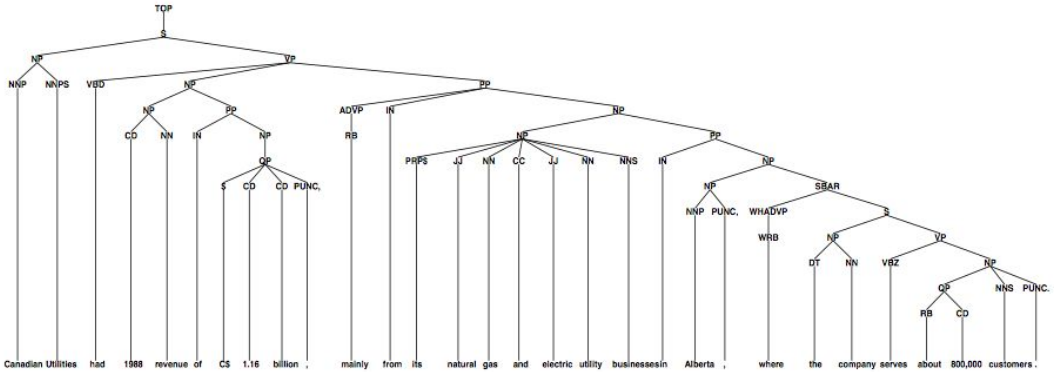
- INPUT:
  - The move followed a round of similar increases by other lenders, reflecting a continuing decline in that market

- OUTPUT:



# A Supervised ML Problem

- Data for parsing experiments:
  - Penn WSJ Treebank = 50,000 sentences with associated trees
  - Usual set-up: 40,000 training, 2,400 test




Canadian Utilities had 1988 revenue of $ 1.16 billion , mainly from its natural gas and electric utility businesses in Alberta , where the company serves about 800,000 customers.

*[from Michael Collins slides]*

# Syntax

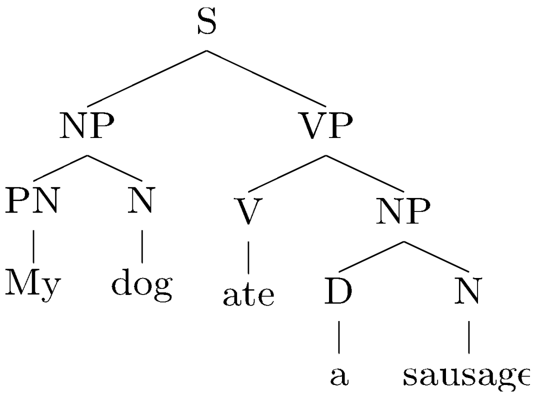
# Syntax

- The study of the patterns of formation of sentences and phrases from words

| | |
|---|---|
| my dog | Pron N |
| the dog | Det N |
| the cat | Det N |
| and | Conj |
| the large cat | Det Adj N |
| the black cat | Det Adj N |
| ate a sausage | V Det N |

# Parsing

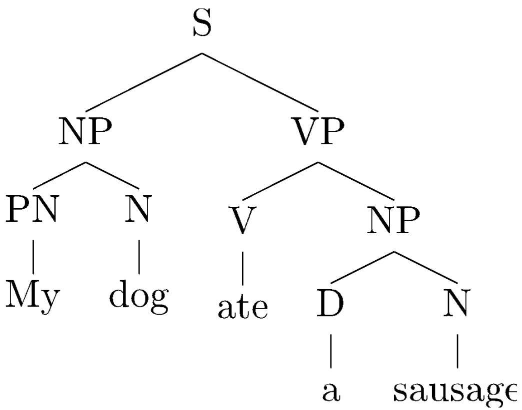
- The process of predicting syntactic representations
- Different types of syntactic representations are possible, for example:




**Constituent (a.k.a. phrase-structure) tree**

# Constituent trees

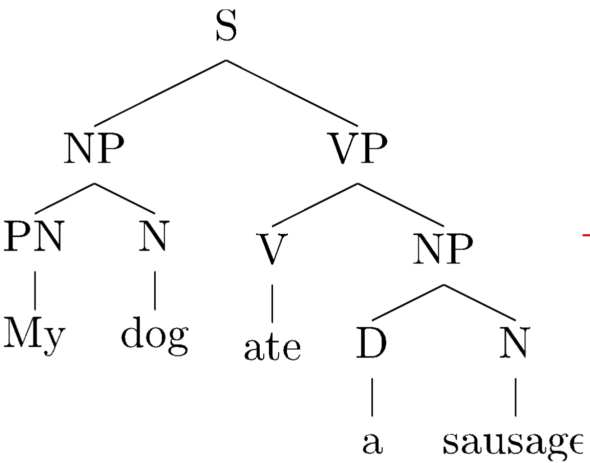
- Internal nodes correspond to phrases
  - S – a sentence
  - NP – Noun Phrase: My dog, a sandwich, lakes,..
  - VP – Verb Phrase: ate a sausage, barked, …
  - PP – Prepositional phrases: with a friend, in a car, …




- Nodes immediately above words are PoS tags (aka preterminals)
  - PN – pronoun
  - D – determiner
  - V – verb
  - N – noun
  - P – preposition

# Bracketing notation

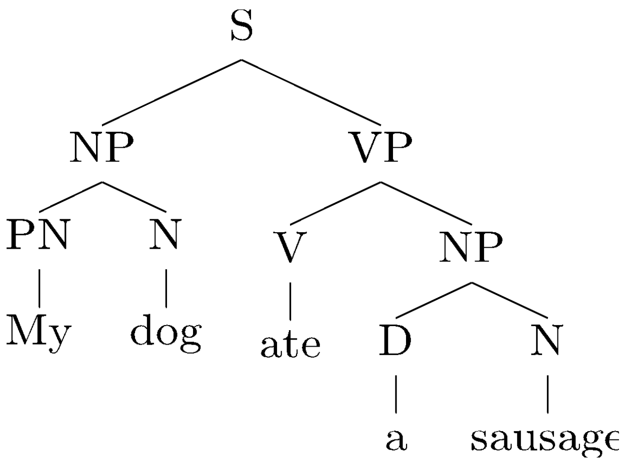
- It is often convenient to represent a tree as a bracketed sequence



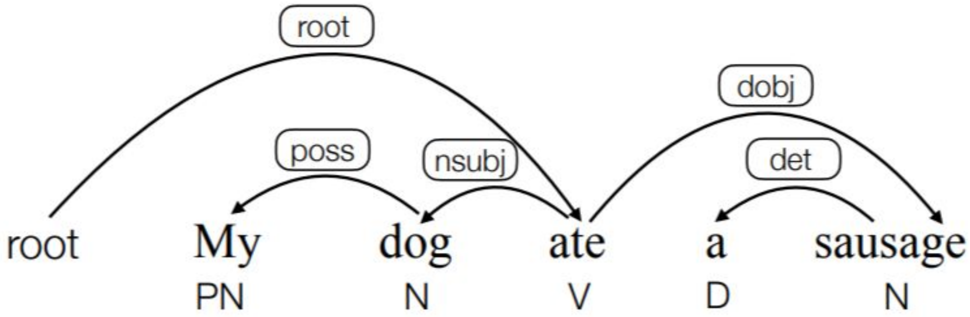

```
(S
   (NP (PN My) (N dog) )
   (VP (V ate)
      (NP (D a) (N sausage) )
   )
)
```

# Parsing

- The process of predicting syntactic representations
- Different types of syntactic representations are possible, for example:



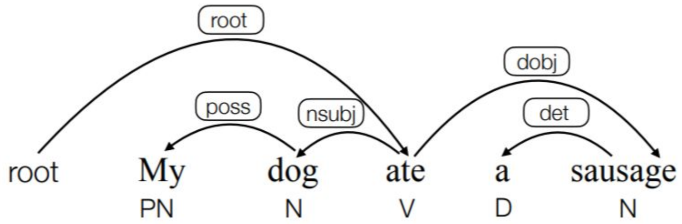

**Constituent (a.k.a. phrase-structure) tree**



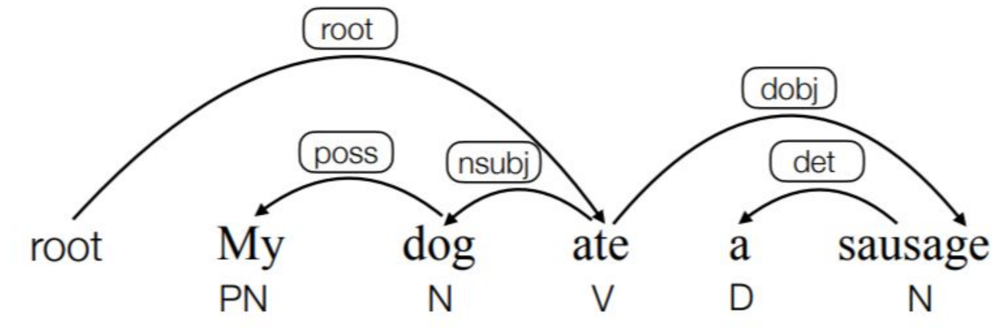

**Dependency tree**

# Dependency trees

- Nodes are words (along with part-of-speech tags)
- Directed arcs encode syntactic dependencies between them
- Labels are types of relations between the words
  - poss – possessive
  - dobj – direct object
  - nsub - subject
  - det - determiner

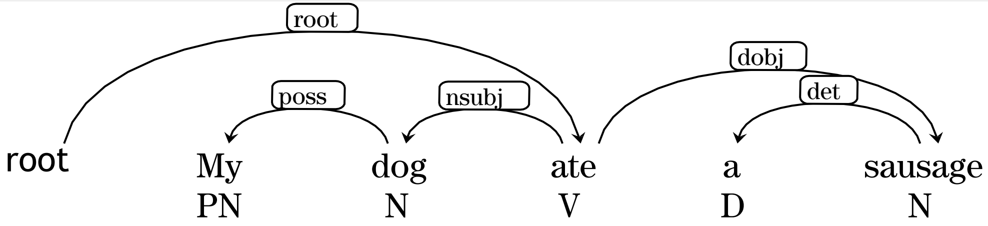


# Recovering shallow semantics




- Some semantic information can be (approximately) derived from syntactic information
  - Subjects (nsubj) are (often) agents ("initiator / doers for an action")
  - Direct objects (dobj) are  (often) patients ("affected entities")

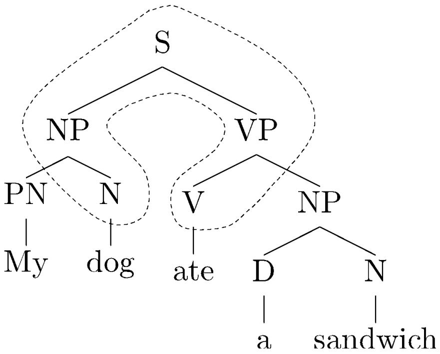
# Recovering shallow semantics



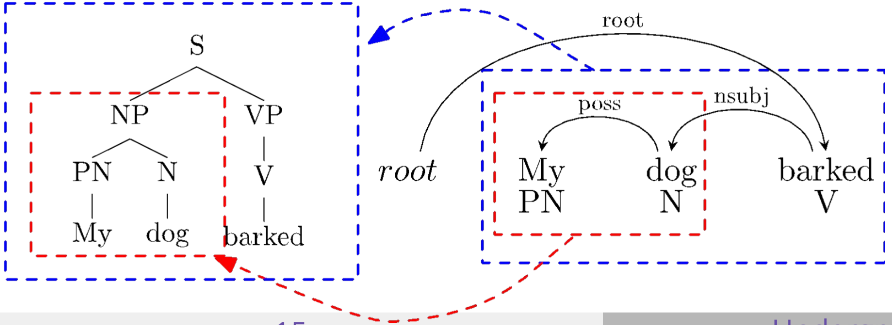

- Some semantic information can be (approximately) derived from syntactic information
  - Subjects (nsubj) are (often) agents ("initiator / doers for an action")
  - Direct objects (dobj) are (often) patients ("affected entities")
- But even for agents and patients consider:
  - Mary is baking a cake in the oven
  - A cake is baking in the oven
- In general it is not trivial even for the most shallow forms of semantics
  - E.g., consider prepositions: *in* can encode direction, position, temporal information, …

# Constituent and dependency representations

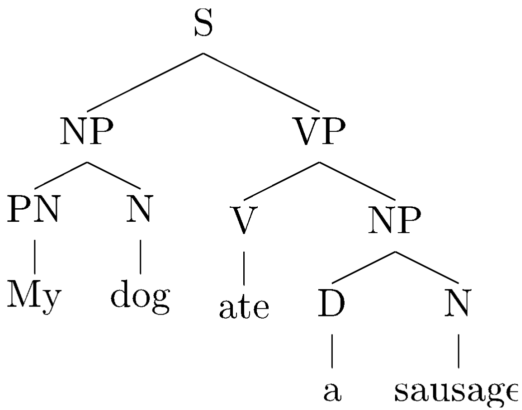
- Constituent trees can (potentially) be converted to dependency trees




- Dependency trees can (potentially) be converted to constituent trees



# Constituent trees

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  - PN – pronoun
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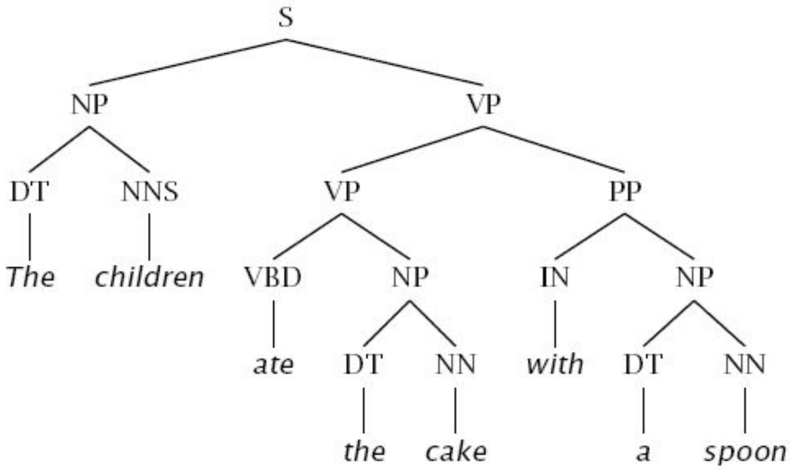
  - V – verb
  - N – noun
  - P – preposition

# Constituency Tests

- How do we know what nodes go in the tree?

- Classic constituency tests:
  - Replacement
  - Movement
    - Passive
    - Clefting
    - Preposing
  - Substitution by *proform*
  - Modification
  - Coordination/Conjunction
  - Ellipsis/Deletion



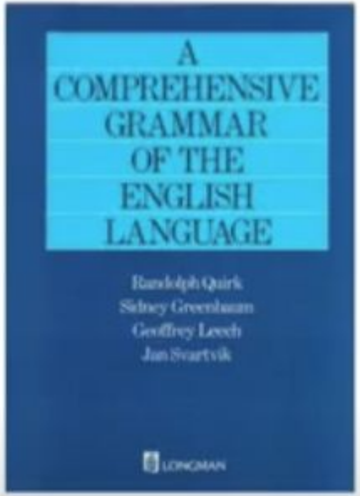
# Morphology/Syntax/Semantics

- Syntax: The study of the patterns of formation of sentences and phrases from word
  - Borders with semantics and morphology sometimes blurred

***Afyonkarahisarlılaştırabildiklerimizdenmişsinizcesinee***

in Turkish means "as if you are one of the people that we thought to be originating from Afyonkarahisar" [wikipedia]

# English grammar

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# Context Free Grammar (CFG)

# Context Free Grammar (CFG)

## Grammar (CFG)

ROOT → S
S → NP VP
NP → DT NN
NP → NN NNS
NP → NP PP
VP → VBP NP
VP → VBP NP PP
PP → IN NP

## Lexicon

NN → interest
NNS → raises
VBP → interest
VBZ → raises
…

Other grammar formalisms: LFG, HPSG, TAG, CCG…

# CFGs

S

$$S \rightarrow NP\ VP$$

$$VP \rightarrow V$$
$$VP \rightarrow V\ NP$$
$$VP \rightarrow VP\ PP$$

$$NP \rightarrow NP\ PP$$
$$NP \rightarrow D\ N$$
$$NP \rightarrow PN$$

$$PP \rightarrow P\ NP$$

$$N \rightarrow girl$$
$$N \rightarrow telescope$$
$$N \rightarrow sandwich$$
$$PN \rightarrow I$$
$$V \rightarrow saw$$
$$V \rightarrow ate$$
$$P \rightarrow with$$
$$P \rightarrow in$$
$$D \rightarrow a$$
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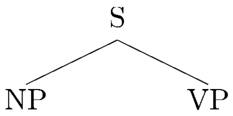
# CFGs

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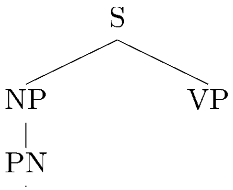


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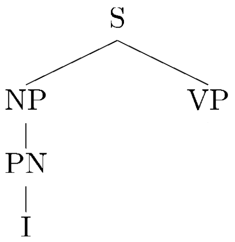


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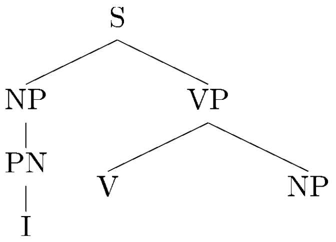


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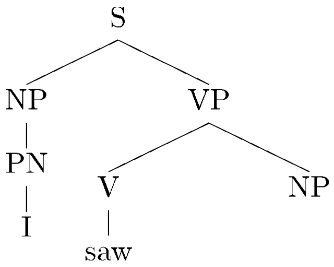


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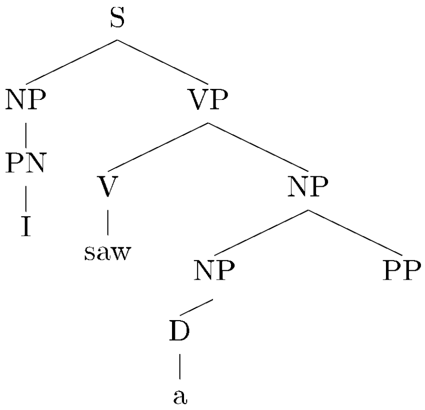


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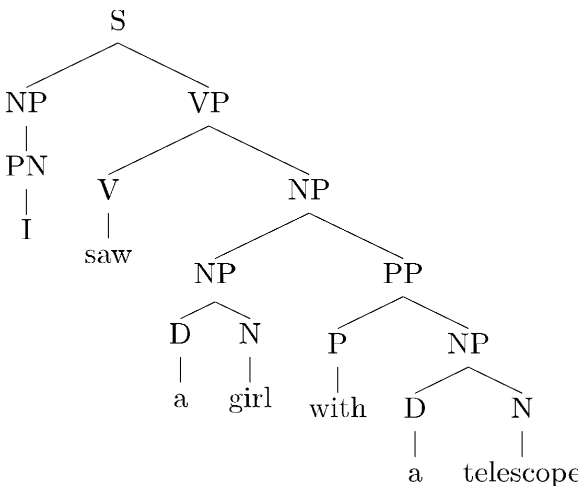


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# Treebank Sentences

```
( (S (NP-SBJ The move)
     (VP followed
         (NP (NP a round)
             (PP of
                 (NP (NP similar increases)
                     (PP by
                         (NP other lenders))
                     (PP against
                         (NP Arizona real estate loans)))))
         ,
         (S-ADV (NP-SBJ *)
                (VP reflecting
                    (NP (NP a continuing decline)
                        (PP-LOC in
                                (NP that market))))))
     .))
```

# Context-Free Grammars

- A context-free grammar is a 4-tuple <N, T, S, R>
  - N : the set of non-terminals
    - **Phrasal categories**: S, NP, VP, ADJP, etc.
    - **Parts-of-speech** (pre-terminals): NN, JJ, DT, VB
  - T : the set of terminals (the words)
  - S : the start symbol
    - Often written as ROOT or TOP
    - Not usually the sentence non-terminal S
  - R : the set of rules
    - Of the form $X \rightarrow Y_1\ Y_2 \ldots Y_k$, with $X, Y_i \in N$
    - Examples: $S \rightarrow NP\ VP$, $VP \rightarrow VP\ CC\ VP$
    - Also called rewrites, productions, or local trees

# An example grammar

$N = \{S, VP, NP, PP, N, V, PN, P\}$

$T = \{girl, telescope, sandwich, I, saw, ate, with, in, a, the\}$

$S = \{S\}$

$R:$

Called **Inner rules**

$S \to NP\ VP$ (NP A girl) (VP ate a sandwich)

$VP \to V$

$VP \to V\ NP$ (V ate) (NP a sandwich)

$VP \to VP\ PP$ (VP saw a girl) (PP with a telescope)

$NP \to NP\ PP$ (NP a girl) (PP with a sandwich)

$NP \to D\ N$ (D a) (N sandwich)

$NP \to PN$

$PP \to P\ NP$ (P with) (NP with a sandwich)

Preterminal rules

$N \to girl$

$N \to telescope$

$N \to sandwich$

$PN \to I$

$V \to saw$

$V \to ate$

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$P \to in$

$D \to a$

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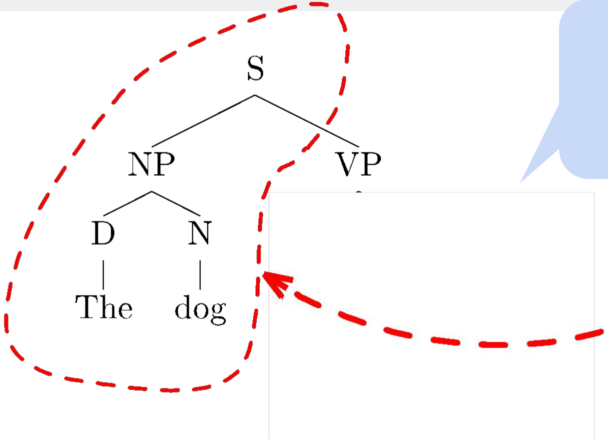
# Why context-free?




What can be a sub-tree is only affected by what the phrase type is (VP) but not the context

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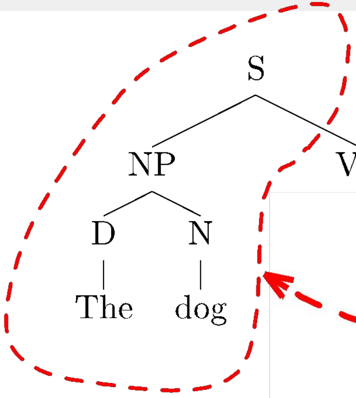


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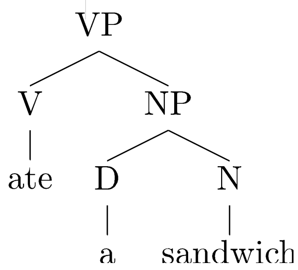
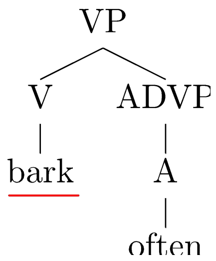


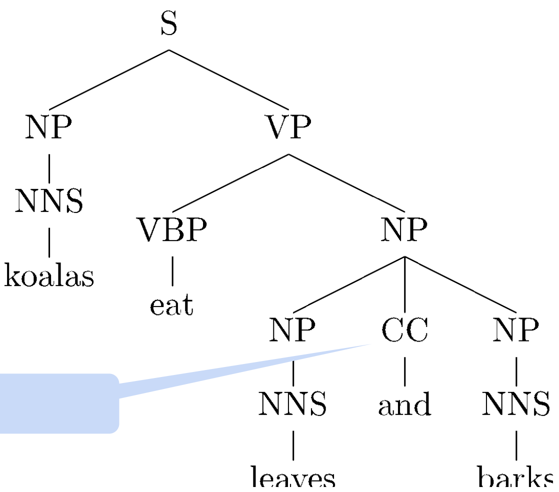




Not grammatical

# Ambiguities

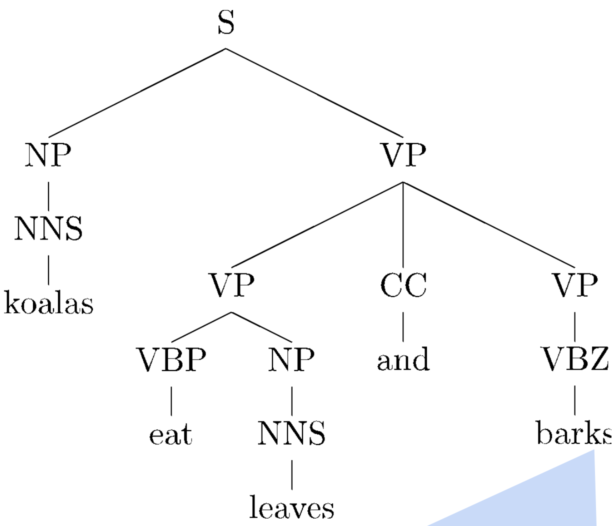
# Coordination ambiguity

- Here, the coarse VP and NP categories cannot enforce subject-verb agreement in number resulting in the coordination ambiguity




Coordination

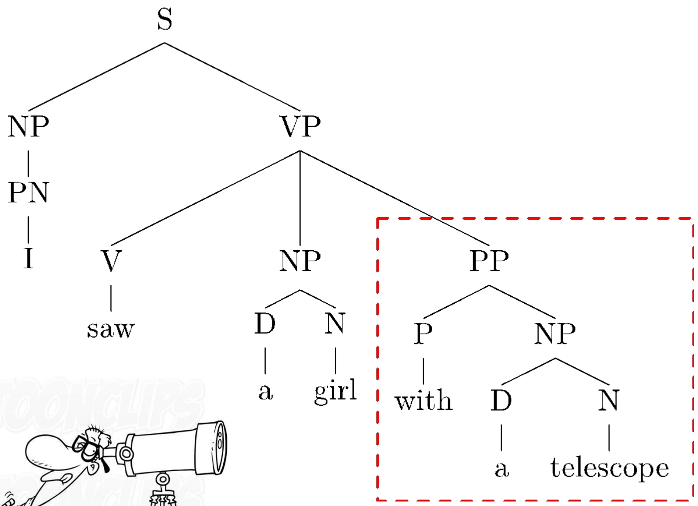
"Bark" can refer both  to a noun or a verb

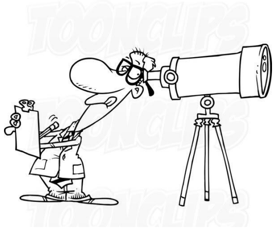


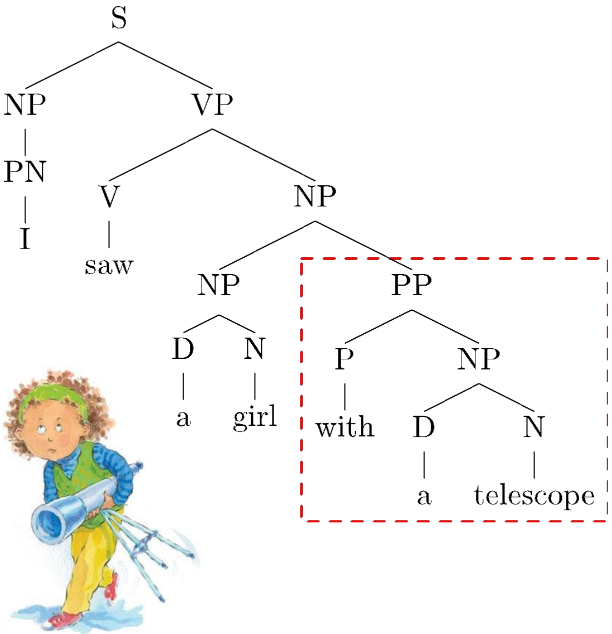

This tree would be ruled out if the context would be somehow captured (subject-verb agreement)

# Why parsing is hard? Ambiguity

- Prepositional phrase attachment ambiguity





# PP Ambiguity

*Put the block in the box on the table in the kitchen*

3 prepositional phrases, 5 interpretations:

- Put the block ((in the box on the table) in the kitchen)
- Put the block (in the box (on the table in the kitchen))
- Put ((the block in the box) on the table) in the kitchen.
- Put (the block (in the box on the table)) in the kitchen.
- Put  (the block in the box) (on the table in the kitchen)

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3 prepositional phrases, 5 interpretations:

- Put the block ((in the box on the table) in the kitchen)
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- …

A general case:

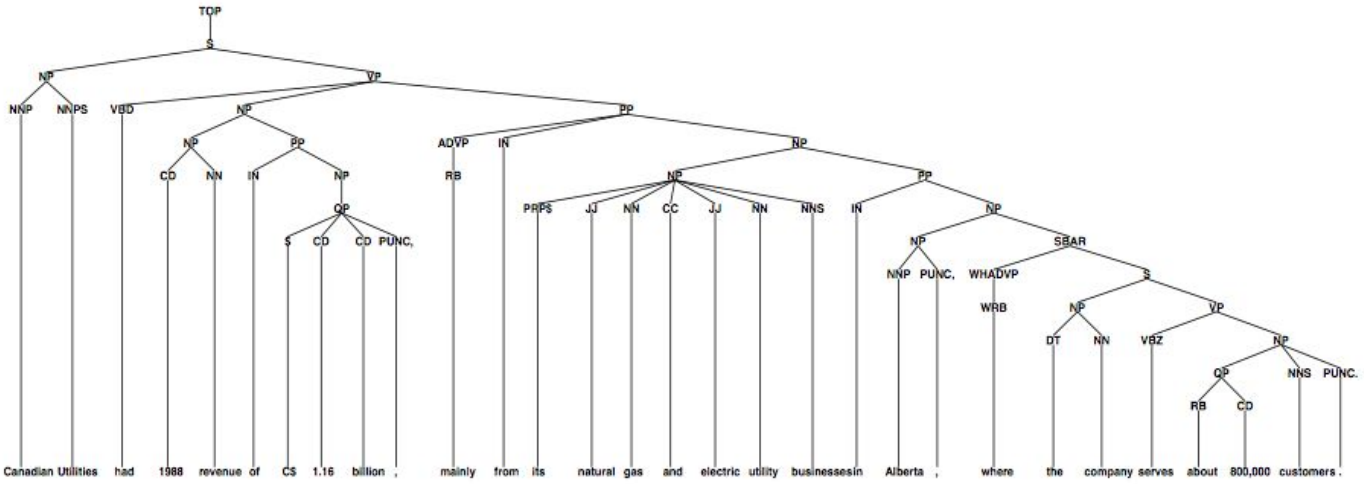
- ((())) ()(()) ()()() (())() (()())

$$Cat_n = \binom{2n}{n} - \binom{2n}{n-1} \sim \frac{4^n}{n^{3/2}\sqrt{\pi}}$$

Catalan numbers

$$1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, \ldots$$

# A typical tree from a standard dataset (Penn treebank WSJ)




Canadian Utilities had 1988 revenue of $ 1.16 billion , mainly from its natural gas and electric utility businesses in Alberta , where the company serves about 800,000 customers .

*[from Michael Collins slides]*

# Syntactic Ambiguities I

- Prepositional phrases:
  - They cooked the beans in the pot on the stove with handles.
- Particle vs. preposition:
  - The puppy tore up the staircase.
- Complement structures
  - The tourists objected to the guide that they couldn't hear.
    She knows you like the back of her hand.
- Gerund vs. participial adjective
  - Visiting relatives can be boring.
    Changing schedules frequently confused passengers.

# Syntactic Ambiguities II

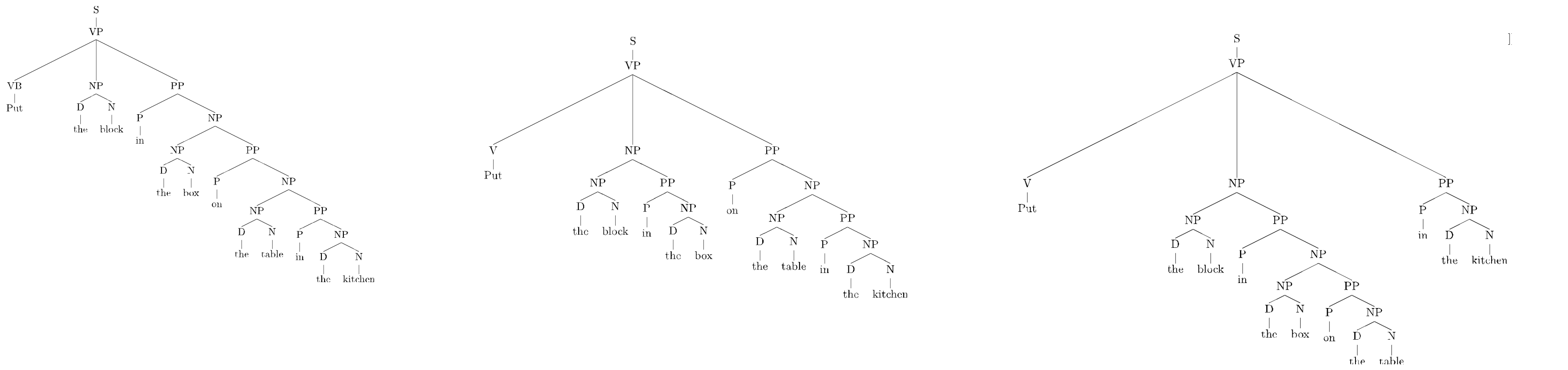
- Modifier scope within NPs
  - impractical design requirements
    plastic cup holder

- Multiple gap constructions
  - The chicken is ready to eat.
    The contractors are rich enough to sue.

- Coordination scope:
  - Small rats and mice can squeeze into holes or cracks in the wall.

# How to Deal with Ambiguity?

- We want to score all the derivations to encode how plausible they are




*Put the block in the box on the table in the kitchen*

# Probabilistic Context Free Grammar (PCFG)

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- A PCFG adds:
  - A top-down production probability per rule $P(Y_1\ Y_2 \ldots Y_k \mid X)$

# PCFGs

Associate probabilities with the rules : $p(X \to \alpha)$

$$\forall \; X \to \alpha \in R: \quad 0 \le p(X \to \alpha) \le 1$$

$$\forall X \in N: \quad \sum_{\alpha: X \to \alpha \in R} p(X \to \alpha) = 1$$

Now we can score a tree as a product of probabilities corresponding to the used rules

| | | |
|---|---|---|
| $S \to NP \;\; VP$ | 1.0 | (NP A girl) (VP ate a sandwich) |
| $VP \to V$ | 0.2 | |
| $VP \to V \;\; NP$ | 0.4 | (VP ate) (NP a sandwich) |
| $VP \to VP \;\; PP$ | 0.4 | (VP saw a girl) (PP with …) |
| $NP \to NP \;\; PP$ | 0.3 | (NP a girl) (PP with ….) |
| $NP \to D \;\; N$ | 0.5 | (D a) (N sandwich) |
| $NP \to PN$ | 0.2 | |
| $PP \to P \;\; NP$ | 1.0 | (P with) (NP with a sandwich) |

| | |
|---|---|
| $N \to girl$ | 0.2 |
| $N \to telescope$ | 0.7 |
| $N \to sandwich$ | 0.1 |
| $PN \to I$ | 1.0 |
| $V \to saw$ | 0.5 |
| $V \to ate$ | 0.5 |
| $P \to with$ | 0.6 |
| $P \to in$ | 0.4 |
| $D \to a$ | 0.3 |
| $D \to the$ | 0.7 |

# PCFGs

S

$$S \rightarrow NP \;\; VP \;\; 1.0$$

$$VP \rightarrow V \;\; 0.2$$
$$VP \rightarrow V \;\; NP \;\; 0.4$$
$$VP \rightarrow VP \;\; PP \;\; 0.4$$

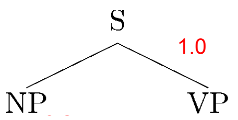
$$NP \rightarrow NP \;\; PP \;\; 0.3$$
$$NP \rightarrow D \;\; N \;\; 0.5$$
$$NP \rightarrow PN \;\; 0.2$$

$$PP \rightarrow P \;\; NP \;\; 1.0$$

$$N \rightarrow girl \;\; 0.2$$
$$N \rightarrow telescope \;\; 0.7$$
$$N \rightarrow sandwich \;\; 0.1$$
$$PN \rightarrow I \;\; 1.0$$
$$V \rightarrow saw \;\; 0.5$$
$$V \rightarrow ate \;\; 0.5$$
$$P \rightarrow with \;\; 0.6$$
$$P \rightarrow in \;\; 0.4$$
$$D \rightarrow a \;\; 0.3$$
$$D \rightarrow the \;\; 0.7$$

$$p(T) =$$

# PCFGs




$$\boxed{S \rightarrow NP\ \ VP\ \ 1.0}$$

$$VP \rightarrow V\ \ 0.2$$
$$VP \rightarrow V\ \ NP\ \ 0.4$$
$$VP \rightarrow VP\ \ PP\ \ 0.4$$

$$NP \rightarrow NP\ \ PP\ \ 0.3$$
$$NP \rightarrow D\ \ N\ \ 0.5$$
$$NP \rightarrow PN\ \ 0.2$$

$$PP \rightarrow P\ \ NP\ \ 1.0$$

$$N \rightarrow girl\ \ 0.2$$
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$$V \rightarrow saw\ \ 0.5$$
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$$P \rightarrow with\ \ 0.6$$
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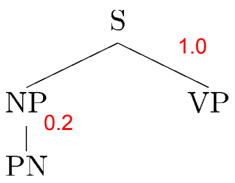
$$D \rightarrow the\ \ 0.7$$

$$p(T) = 1.0 \times$$

# PCFGs




$S \rightarrow NP \;\; VP$ 1.0

$VP \rightarrow V$ 0.2
$VP \rightarrow V \;\; NP$ 0.4
$VP \rightarrow VP \;\; PP$ 0.4

$NP \rightarrow NP \;\; PP$ 0.3
$NP \rightarrow D \;\; N$ 0.5
$\boxed{NP \rightarrow PN \;\; 0.2}$

$PP \rightarrow P \;\; NP$ 1.0

$N \rightarrow girl$ 0.2
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$D \rightarrow a$ 0.3
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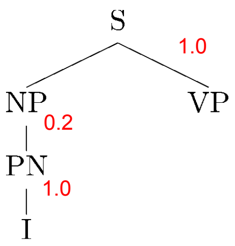
$$p(T) = 1.0 \times 0.2 \times$$

# PCFGs

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$VP \rightarrow V$ 0.2

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$NP \rightarrow PN$ 0.2

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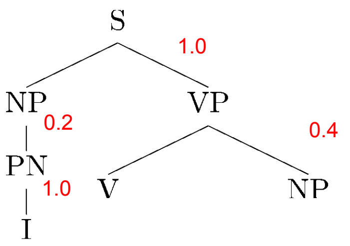
$$p(T) = 1.0 \times 0.2 \times 1.0 \times$$

# PCFGs




$S \rightarrow NP \;\; VP$ 1.0

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$\boxed{VP \rightarrow V \;\; NP \;\; 0.4}$

$VP \rightarrow VP \;\; PP$ 0.4

$NP \rightarrow NP \;\; PP$ 0.3

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$NP \rightarrow PN$ 0.2

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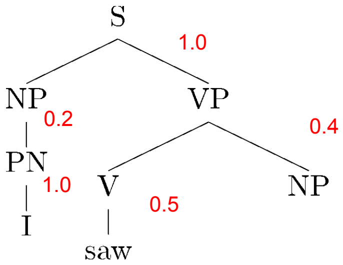
$D \rightarrow a$ 0.3

$D \rightarrow the$ 0.7

$$p(T) = 1.0 \times 0.2 \times 1.0 \times 0.4 \times$$

# PCFGs




$S \rightarrow NP\ VP$ 1.0

$VP \rightarrow V$ 0.2
$VP \rightarrow V\ NP$ 0.4
$VP \rightarrow VP\ PP$ 0.4

$NP \rightarrow NP\ PP$ 0.3
$NP \rightarrow D\ N$ 0.5
$NP \rightarrow PN$ 0.2

$PP \rightarrow P\ NP$ 1.0

$N \rightarrow girl$ 0.2
$N \rightarrow telescope$ 0.7
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$\boxed{V \rightarrow saw\ 0.5}$
$V \rightarrow ate$ 0.5
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$P \rightarrow in$ 0.4
$D \rightarrow a$ 0.3
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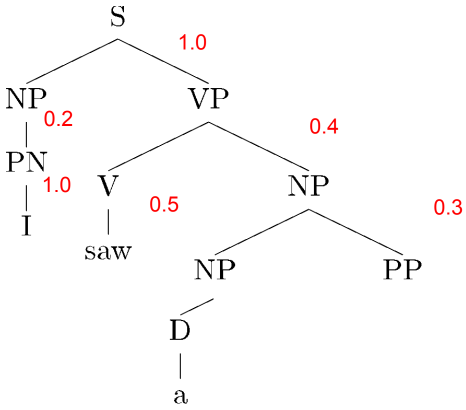
$$p(T) = 1.0 \times 0.2 \times 1.0 \times 0.4 \times 0.5 \times$$

# PCFGs




$S \rightarrow NP\ \ VP$ 1.0

$VP \rightarrow V$ 0.2

$VP \rightarrow V\ \ NP$ 0.4

$VP \rightarrow VP\ \ PP$ 0.4

$\boxed{NP \rightarrow NP\ \ PP\ \ 0.3}$

$NP \rightarrow D\ \ N$ 0.5

$NP \rightarrow PN$ 0.2

$PP \rightarrow P\ \ NP$ 1.0

$N \rightarrow girl$ 0.2

$N \rightarrow telescope$ 0.7

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$D \rightarrow a$ 0.3

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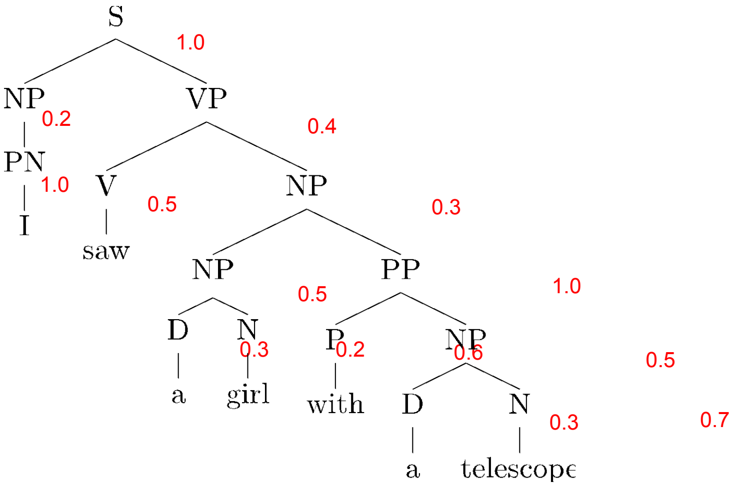
$$p(T) = 1.0 \times 0.2 \times 1.0 \times 0.4 \times 0.5 \times 0.3 \times$$

# PCFGs




$S \rightarrow NP\ \ VP$ 1.0

$VP \rightarrow V$ 0.2

$VP \rightarrow V\ \ NP$ 0.4

$VP \rightarrow VP\ \ PP$ 0.4

$NP \rightarrow NP\ \ PP$ 0.3

$NP \rightarrow D\ \ N$ 0.5

$NP \rightarrow PN$ 0.2

$PP \rightarrow P\ \ NP$ 1.0

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$D \rightarrow a$ 0.3

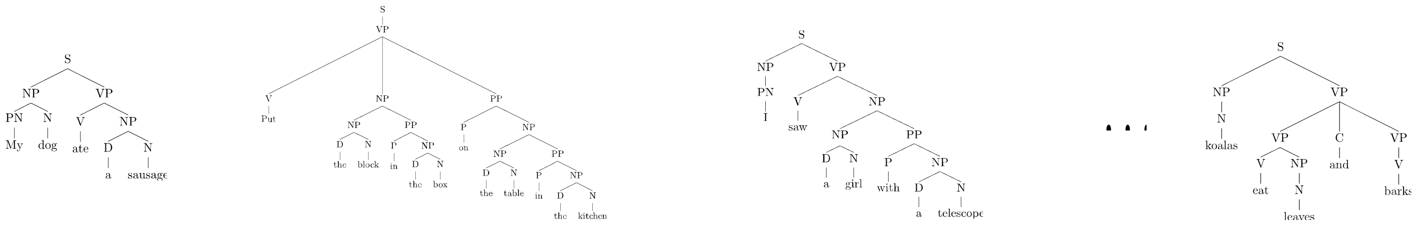
$D \rightarrow the$ 0.7

$$p(T) = 1.0 \times 0.2 \times 1.0 \times 0.4 \times 0.5 \times 0.3 \times 0.5 \times 0.3 \times 0.2 \times 1.0 \times 0.6 \times 0.5 \times 0.3 \times 0.7 = 2.26 \times 10^{-5}$$

# PCFG Estimation

# ML estimation

- A treebank: a collection sentences annotated with constituent trees




- An estimated probability of a rule (maximum likelihood estimates)

$$p(X \rightarrow \alpha) = \frac{C(X \rightarrow \alpha)}{C(X)}$$

The number of times the rule used in the corpus

The number of times the nonterminal X appears in the treebank

- Smoothing is helpful
  - Especially important for preterminal rules

# Parsing evaluation

# Parsing evaluation

- Intrinsic evaluation:
  - Automatic: evaluate against annotation provided by human experts (gold standard) according to some predefined measure
  - Manual: … according to human judgment

- Extrinsic evaluation: score syntactic representation by comparing how well a system using this representation performs on some task
  - E.g., use syntactic representation as input for a semantic analyzer and compare results of the analyzer using syntax predicted by different parsers.

# Standard evaluation setting in parsing

- Automatic intrinsic evaluation is used: parsers are evaluated against gold standard by provided by linguists
  - There is a standard split into the parts:
    - training set: used for estimation of model parameters
    - development set: used for tuning the model (initial experiments)
    - test set: final experiments to compare against previous work

# Automatic evaluation of constituent parsers

- Exact match: percentage of trees predicted correctly
- Bracket score: scores how well individual phrases (and their boundaries) are identified

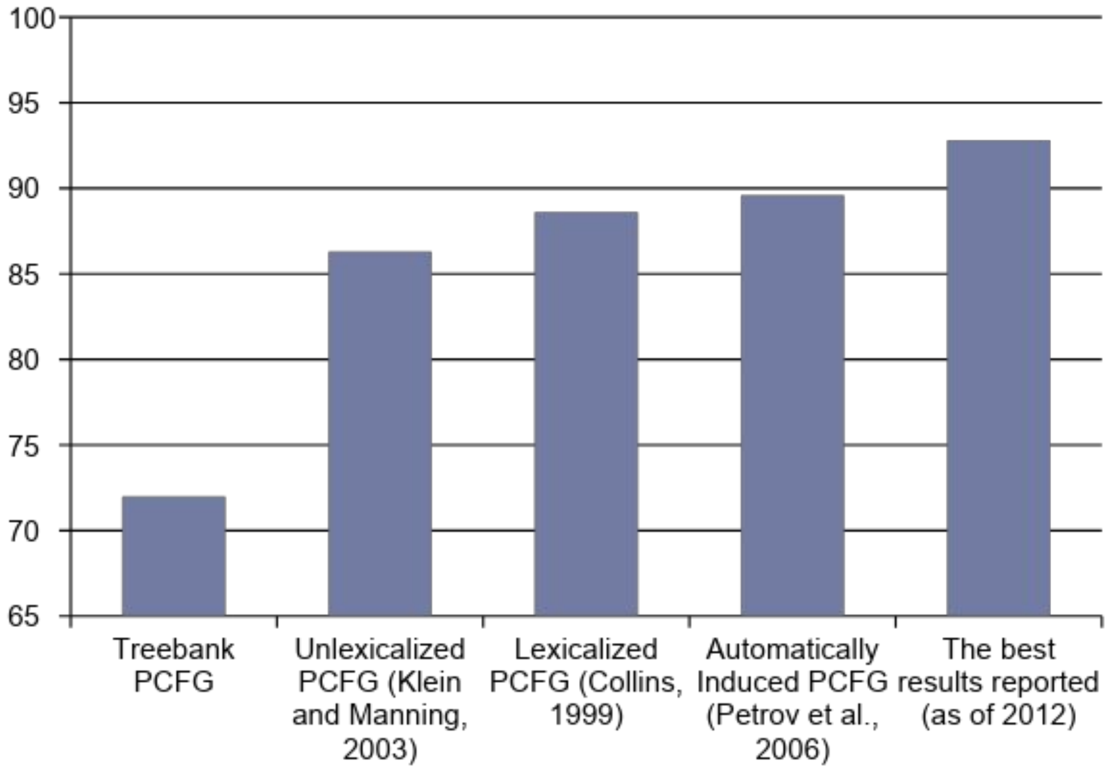
The most standard measure; we will focus on it

# Brackets scores

Subtree signatures for CKY

- The most standard score is bracket score
- It regards a tree as a collection of brackets: $[min, max, C]$
- The set of brackets predicted by a parser is compared against the set of brackets in the tree annotated by a linguist
- Precision, recall and F1 are used as scores

# Preview: F1 bracket score



# CKY Parsing

# Parsing

- Parsing is search through the space of all possible parses
  - e.g., we may want either any parse, all parses or the highest scoring parse (if PCFG):

$$\arg\max_{T \in G(x)} P(T)$$

- Bottom-up:
  - One starts from words and attempt to construct the full tree

- Top-down
  - Start from the start symbol and attempt to expand to get the sentence

# CKY algorithm (aka CYK)

- Cocke-Kasami-Younger algorithm
  - Independently discovered in late 60s / early 70s

- An efficient bottom up parsing algorithm for (P)CFGs
  - can be used both for the recognition and parsing problems
  - Very important in NLP (and beyond)

- We will start with the non-probabilistic version

# Constraints on the grammar

- The basic CKY algorithm supports only rules in the Chomsky Normal Form (CNF):

$$C \rightarrow x$$

Unary preterminal rules (generation of words given PoS tags) $N \rightarrow telescope$ $D \rightarrow the$

$$C \rightarrow C_1 C_2$$

Binary inner rules $S \rightarrow NP\ VP$ $NP \rightarrow D\ N$

# Constraints on the grammar

- The basic CKY algorithm supports only rules in the Chomsky Normal Form (CNF):

$$C \to x$$

$$C \to C_1 C_2$$

- Any CFG can be converted to an equivalent CNF
  - Equivalent means that they define the same language
  - However (syntactic) trees will look differently
  - It is possible to address it by defining such transformations that allows for easy reverse transformation

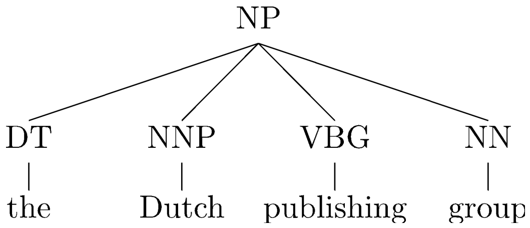
# Transformation to CNF form

- What one need to do to convert to CNF form
  - Get rid of rules that mix terminals and non-terminals
  - Get rid of unary rules: $C \rightarrow C_1$
  - Get rid of N-ary rules: $C \rightarrow C_1\ C_2 \ldots C_n \quad (n > 2)$

Crucial to process them, as required for efficient parsing

# Transformation to CNF form: binarization

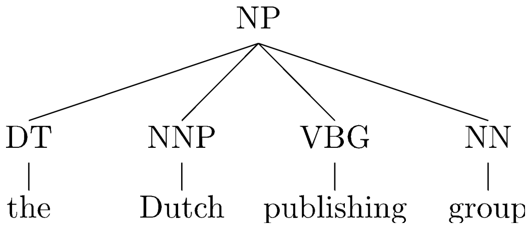
- Consider $NP \rightarrow DT\ \ NNP\ \ VBG\ \ NN$




- How do we get a set of binary rules which are equivalent?

# Transformation to CNF form: binarization

- Consider $NP \rightarrow DT \;\; NNP \;\; VBG \;\; NN$

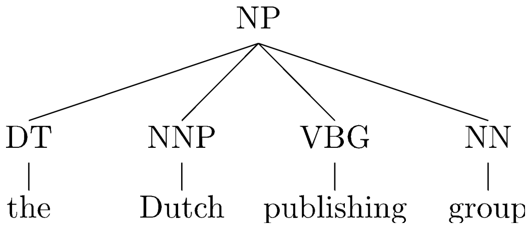



- How do we get a set of binary rules which are equivalent?

$$NP \rightarrow DT \;\; X$$
$$X \rightarrow NNP \;\; Y$$
$$Y \rightarrow VBG \;\; NN$$

# Transformation to CNF form: binarization

- Consider $NP \rightarrow DT \;\; NNP \;\; VBG \;\; NN$




- How do we get a set of binary rules which are equivalent?

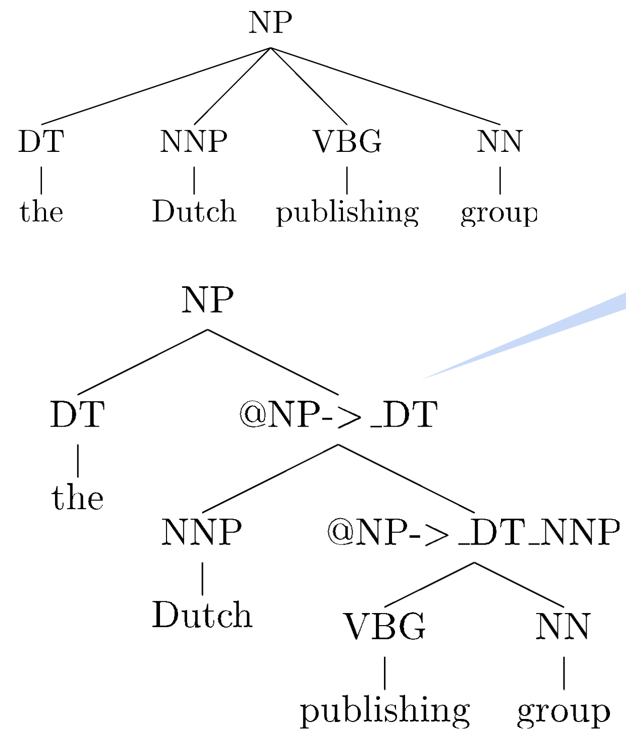
$$NP \rightarrow DT \;\; X$$
$$X \rightarrow NNP \;\; Y$$
$$Y \rightarrow VBG \;\; NN$$

- A more systematic way to refer to new non-terminals

$$NP \rightarrow DT \;\; @NP|DT$$
$$@NP|DT \rightarrow NNP \;\; @NP|DT\_NNP$$
$$@NP|DT\_NNP \rightarrow VBG \;\; NN$$

# Transformation to CNF form: binarization

- Instead of binarizing tuples we can binarize trees on preprocessing:




Also known as **lossless Markovization** in the context of PCFGs

Can be easily reversed on postprocessing

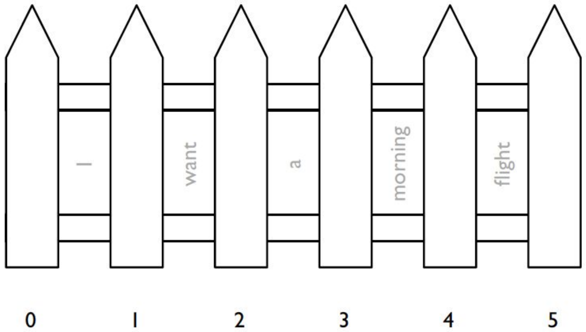
# CKY: Parsing task

- We are given
  - a grammar <N, T, S, R>
  - a sequence of words $\boldsymbol{w} = (w_1, w_2, \ldots, w_n)$

- Our goal is to produce a parse tree for $w$

# CKY: Parsing task

- We a given
  - a grammar <N, T, S, R>
  - a sequence of words $\boldsymbol{w} = (w_1, w_2, \ldots, w_n)$
- Our goal is to produce a parse tree for $w$
- We need an easy way to refer to substrings of $w$




indices refer to fenceposts

span (i, j) refers to words between fenceposts i and j

# Parsing one word

$$C \rightarrow w_i$$

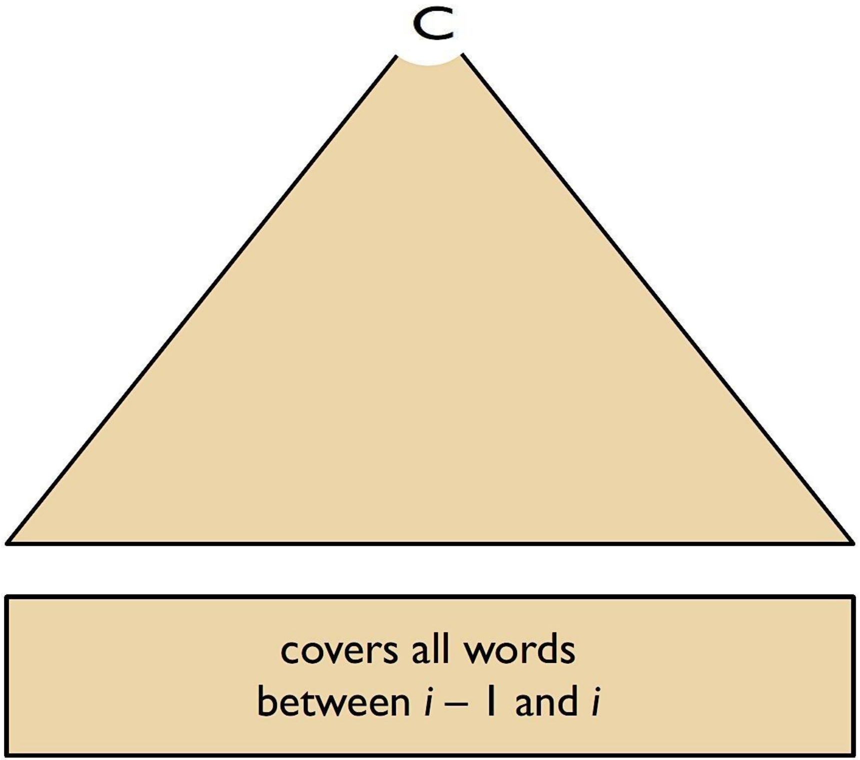
$w_i$

# Parsing one word

$$C \rightarrow w_i$$

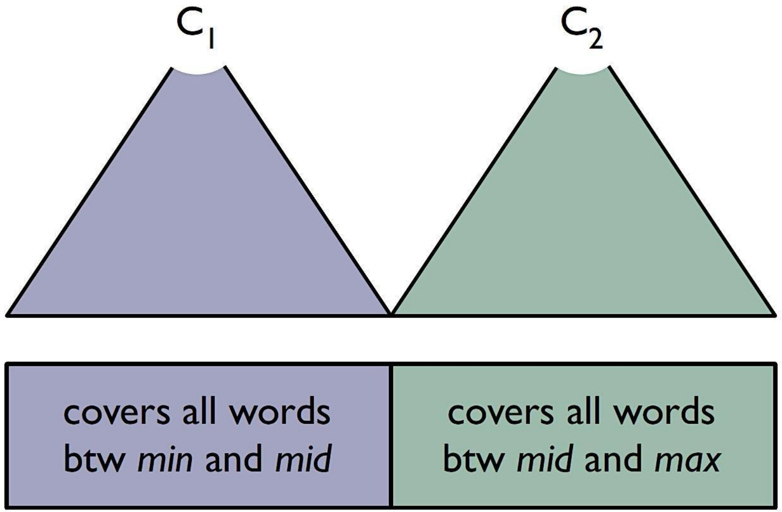
# Parsing one word

$$C \rightarrow w_i$$



# Parsing longer spans

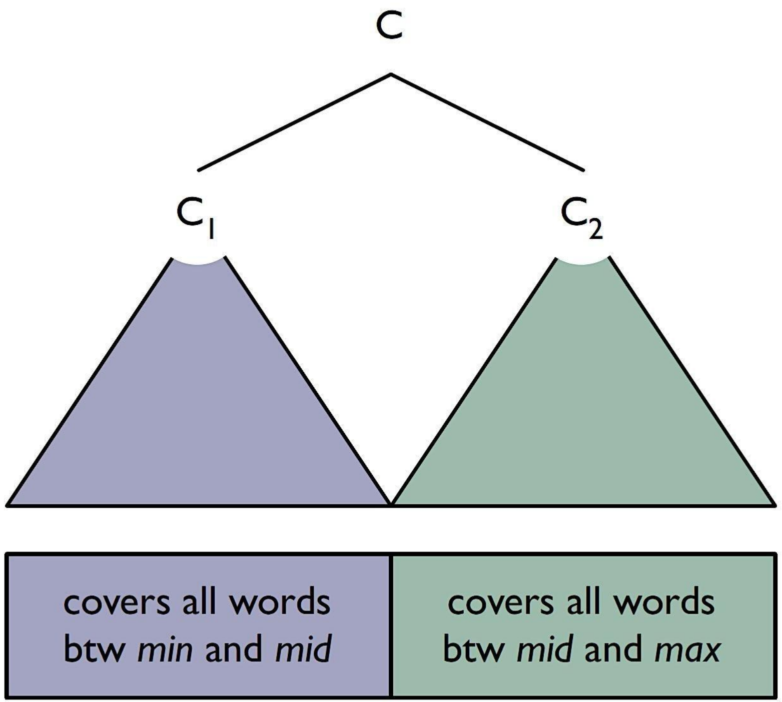
$$C \rightarrow C_1 \;\; C_2$$




Check through all C1, C2, mid

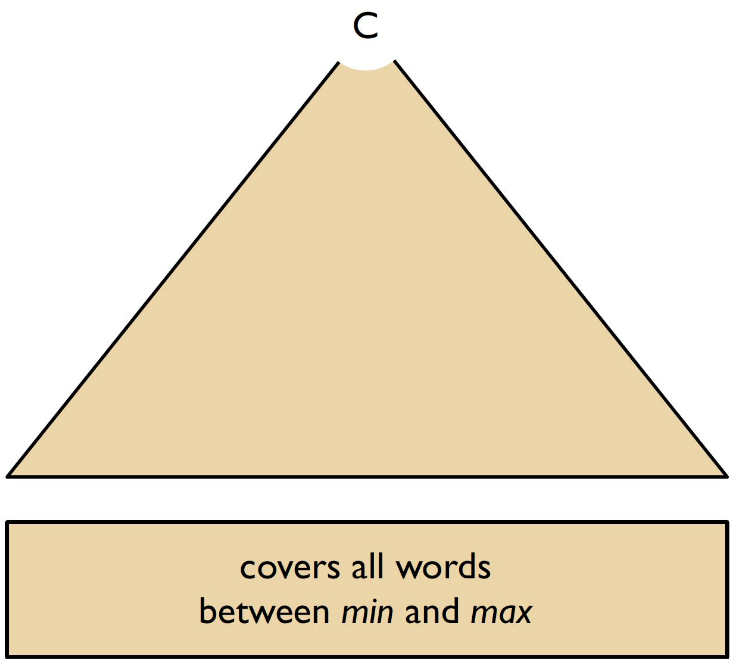
# Parsing longer spans

$$C \rightarrow C_1 \;\; C_2$$




Check through all C1, C2, mid

# Parsing longer spans



| lead | can | poison |
0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | | | $S?$ |
| min = 1 | | | |
| min = 2 | | | |

Chart (aka parsing triangle)

$$S \rightarrow NP\ VP$$

$$VP \rightarrow M\ V$$
$$VP \rightarrow V$$

$$NP \rightarrow N$$
$$NP \rightarrow N\ NP$$

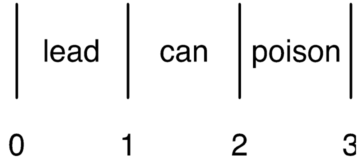
Inner rules

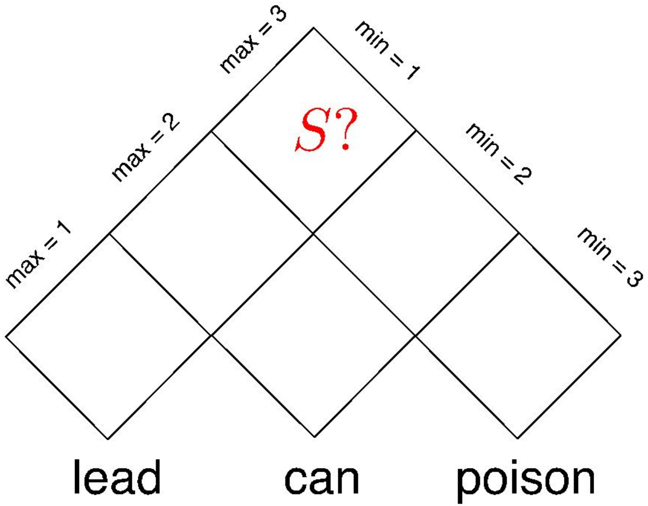
$$N \rightarrow can$$
$$N \rightarrow lead$$
$$N \rightarrow poison$$

$$M \rightarrow can$$
$$M \rightarrow must$$

$$V \rightarrow poison$$
$$V \rightarrow lead$$

Preterminal rules

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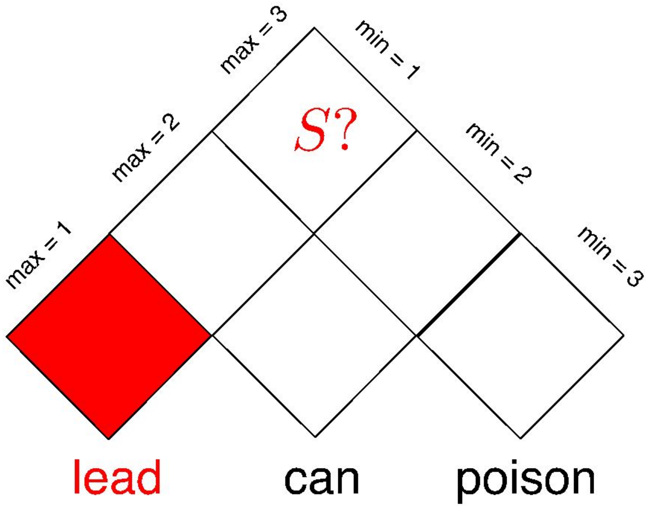


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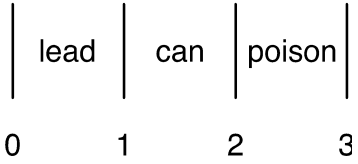


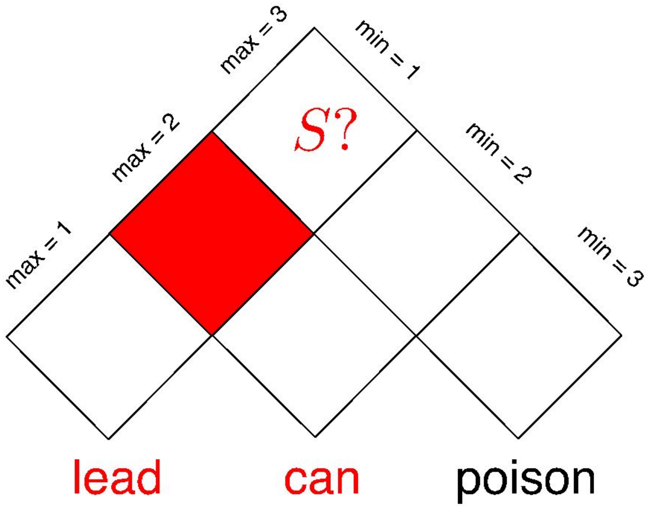


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Inner rules

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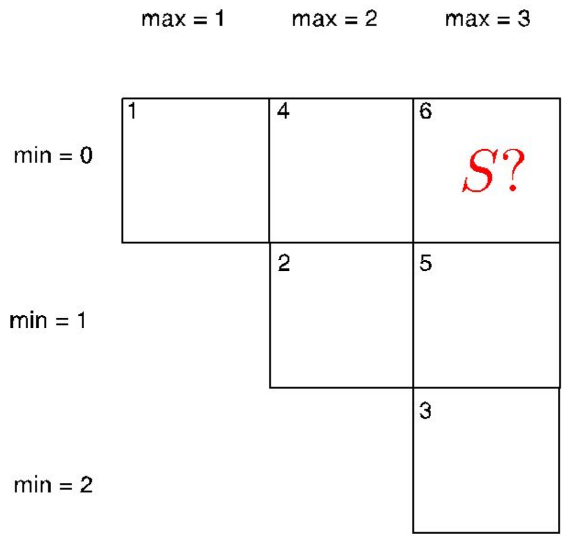
0 1 2 3

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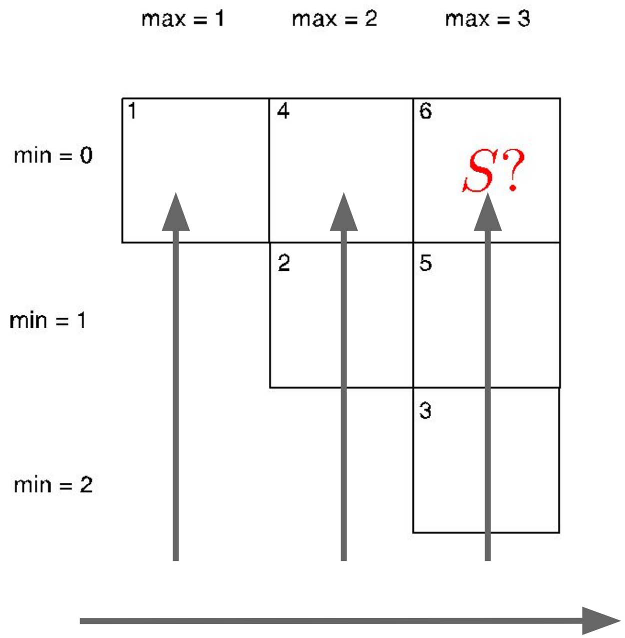


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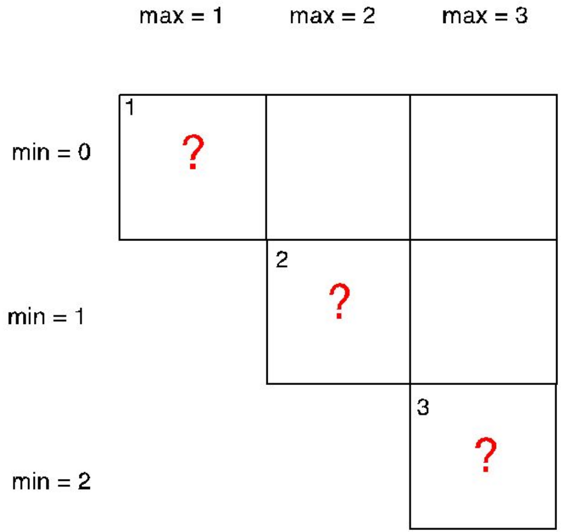


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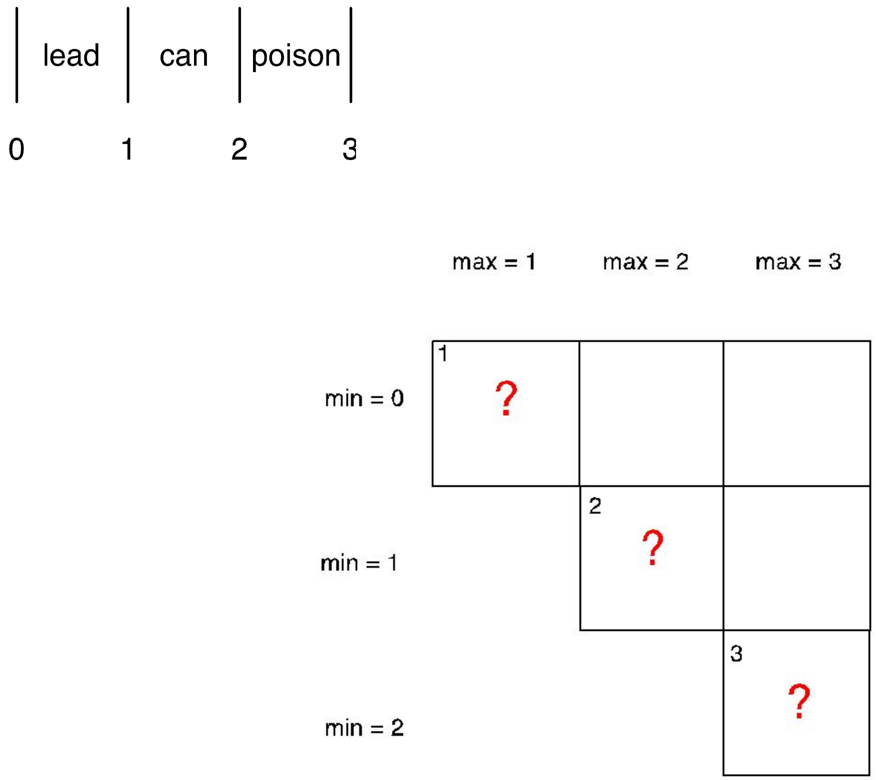



$$S \rightarrow NP\ VP$$

$$VP \rightarrow M\ V$$
$$VP \rightarrow V$$

$$NP \rightarrow N$$
$$NP \rightarrow N\ NP$$

Inner rules

$$N \rightarrow can$$
$$N \rightarrow lead$$
$$N \rightarrow poison$$

$$M \rightarrow can$$
$$M \rightarrow must$$

$$V \rightarrow poison$$
$$V \rightarrow lead$$

Preterminal rules

| lead | can | poison |
|---|---|---|

0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ | | |
| min = 1 | | 2 $N, M$ | |
| min = 2 | | | 3 $N, V$ |

$$S \rightarrow NP\ VP$$

$$VP \rightarrow M\ V$$

$$VP \rightarrow V$$

$$NP \rightarrow N$$

$$NP \rightarrow N\ NP$$

Inner rules

$$N \rightarrow can$$

$$N \rightarrow lead$$

$$N \rightarrow poison$$

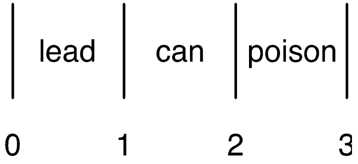
$$M \rightarrow can$$

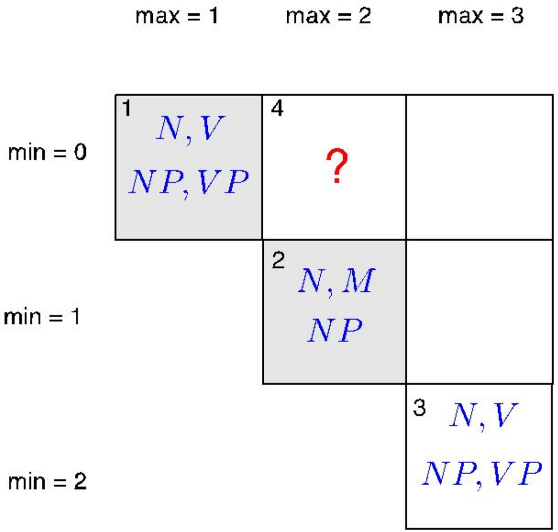
$$M \rightarrow must$$

$$V \rightarrow poison$$

$$V \rightarrow lead$$

Preterminal rules




$S \rightarrow NP\ VP$

$VP \rightarrow M\ V$

$VP \rightarrow V$

$NP \rightarrow N$

$NP \rightarrow N\ NP$

Inner rules

$N \rightarrow can$

$N \rightarrow lead$

$N \rightarrow poison$

$M \rightarrow can$

$M \rightarrow must$

$V \rightarrow poison$

$V \rightarrow lead$

Preterminal rules

| lead | can | poison |
0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ $NP, VP$ | 4 ? | |
| min = 1 | | 2 $N, M$ $NP$ | |
| min = 2 | | | 3 $N, V$ $NP, VP$ |

$$S \rightarrow NP\ VP$$

Inner rules

$$VP \rightarrow M\ V$$
$$VP \rightarrow V$$
$$NP \rightarrow N$$
$$\boxed{NP \rightarrow N\ NP}$$

Preterminal rules

$$N \rightarrow can$$
$$N \rightarrow lead$$
$$N \rightarrow poison$$
$$M \rightarrow can$$
$$M \rightarrow must$$
$$V \rightarrow poison$$
$$V \rightarrow lead$$

| lead | can | poison |
|---|---|---|

0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ <br> $NP, VP$ | 4 $NP$ | |
| min = 1 | | 2 $N, M$ <br> $NP$ | |
| min = 2 | | | 3 $N, V$ <br> $NP, VP$ |

Inner rules

$$S \rightarrow NP \ VP$$

$$VP \rightarrow M \ V$$

$$VP \rightarrow V$$

$$NP \rightarrow N$$

$$\boxed{NP \rightarrow N \ NP}$$

Preterminal rules

$$N \rightarrow can$$

$$N \rightarrow lead$$

$$N \rightarrow poison$$

$$M \rightarrow can$$

$$M \rightarrow must$$

$$V \rightarrow poison$$

$$V \rightarrow lead$$

| lead | can | poison |

0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ $NP, VP$ | 4 $NP$ | |
| min = 1 | | 2 $N, M$ $NP$ | 5 ? |
| min = 2 | | | 3 $N, V$ $NP, VP$ |

Inner rules

$$S \rightarrow NP\ VP$$

$$VP \rightarrow M\ V$$

$$VP \rightarrow V$$

$$NP \rightarrow N$$

$$NP \rightarrow N\ NP$$

Preterminal rules

$$N \rightarrow can$$

$$N \rightarrow lead$$

$$N \rightarrow poison$$

$$M \rightarrow can$$

$$M \rightarrow must$$

$$V \rightarrow poison$$

$$V \rightarrow lead$$

| lead | can | poison |
0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ $NP, VP$ | 4 $NP$ | |
| min = 1 | | 2 $N, M$ $NP$ | 5 $S, VP,$ $NP$ |
| min = 2 | | | 3 $N, V$ $NP, VP$ |

Inner rules

$$\boxed{S \rightarrow NP\ VP}$$

$$\boxed{VP \rightarrow M\ V}$$

$$VP \rightarrow V$$

$$NP \rightarrow N$$

$$\boxed{NP \rightarrow N\ NP}$$

Preterminal rules

$$N \rightarrow can$$
$$N \rightarrow lead$$
$$N \rightarrow poison$$

$$M \rightarrow can$$
$$M \rightarrow must$$

$$V \rightarrow poison$$
$$V \rightarrow lead$$

| lead | can | poison |
0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ $NP, VP$ | 4 $NP$ | 6 ? |
| min = 1 | | 2 $N, M$ $NP$ | 5 $S, VP,$ $NP$ |
| min = 2 | | | 3 $N, V$ $NP, VP$ |

Inner rules

$$S \rightarrow NP\ VP$$

$$VP \rightarrow M\ V$$
$$VP \rightarrow V$$

$$NP \rightarrow N$$
$$NP \rightarrow N\ NP$$

Preterminal rules

$$N \rightarrow can$$
$$N \rightarrow lead$$
$$N \rightarrow poison$$

$$M \rightarrow can$$
$$M \rightarrow must$$

$$V \rightarrow poison$$
$$V \rightarrow lead$$

| lead | can | poison |

0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ <br> $NP, VP$ | 4 $NP$ | 6 ? |
| min = 1 | | 2 $N, M$ <br> $NP$ | 5 $S, VP,$ <br> $NP$ |
| min = 2 | | | 3 $N, V$ <br> $NP, VP$ |

Inner rules

$$S \rightarrow NP \ VP$$

$$VP \rightarrow M \ V$$

$$VP \rightarrow V$$

$$NP \rightarrow N$$

$$NP \rightarrow N \ NP$$

Preterminal rules

$$N \rightarrow can$$

$$N \rightarrow lead$$

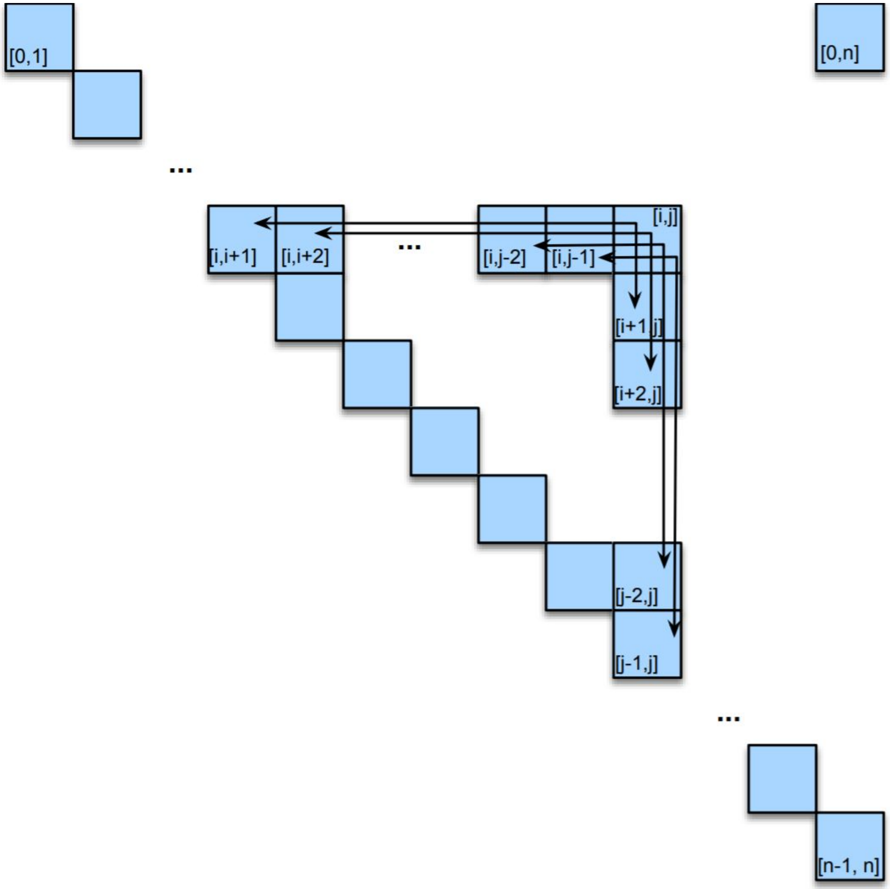
$$N \rightarrow poison$$

$$M \rightarrow can$$

$$M \rightarrow must$$

$$V \rightarrow poison$$

$$V \rightarrow lead$$


[0,1]
[0,n]
...
[i,j]
[i,i+1]
[i,i+2]
...
[i,j-2]
[i,j-1]
[i+1,j]
[i+2,j]
[j-2,j]
[j-1,j]
...
[n-1, n]

| lead | can | poison |
|---|---|---|

0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ $NP, VP$ | 4 $NP$ | 6 $S$, $NP$ |
| min = 1 | | 2 $N, M$ $NP$ | 5 $S, VP,$ $NP$ |
| min = 2 | | | 3 $N, V$ $NP, VP$ |

mid=1

$S \to NP\ VP$

Inner rules

$VP \to M\ V$

$VP \to V$

$NP \to N$

$NP \to N\ NP$

Preterminal rules

$N \to can$

$N \to lead$

$N \to poison$

$M \to can$

$M \to must$

$V \to poison$

$V \to lead$

$\boxed{S \rightarrow NP\ VP}$

| lead | can | poison |

0 1 2 3

mid=2

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ $NP, VP$ | 4 $NP$ | 6 $S$, $NP$ $S(?!)$ |
| min = 1 | | 2 $N, M$ $NP$ | 5 $S, VP,$ $NP$ |
| min = 2 | | | 3 $N, V$ $NP, VP$ |

Inner rules

$$VP \rightarrow M\ V$$
$$VP \rightarrow V$$
$$NP \rightarrow N$$
$$NP \rightarrow N\ NP$$

Preterminal rules

$$N \rightarrow can$$
$$N \rightarrow lead$$
$$N \rightarrow poison$$
$$M \rightarrow can$$
$$M \rightarrow must$$
$$V \rightarrow poison$$
$$V \rightarrow lead$$

| lead | can | poison |
|---|---|---|

0 1 2 3

| | max = 1 | max = 2 | max = 3 |
|---|---|---|---|
| min = 0 | 1 $N, V$ $NP, VP$ | 4 $NP$ | 6 $S$, $NP$ $S(?!)$ |
| min = 1 | | 2 $N, M$ $NP$ | 5 $S, VP,$ $NP$ |
| min = 2 | | | 3 $N, V$ $NP, VP$ |

Inner rules

$$\boxed{S \to NP\ VP}$$

$$VP \to M\ V$$
$$VP \to V$$

$$NP \to N$$
$$NP \to N\ NP$$

Preterminal rules

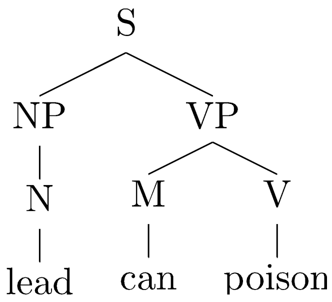
$$N \to can$$
$$N \to lead$$
$$N \to poison$$

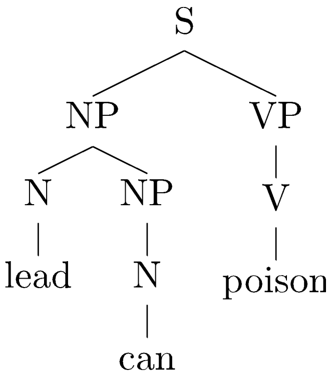
$$M \to can$$
$$M \to must$$

$$V \to poison$$
$$V \to lead$$

Apparently the sentence is ambiguous for the grammar: (as the grammar overgenerates)

# Ambiguity




No subject-verb agreement, and *poison* used as an intransitive verb