6.864: Lecture 2, Fall 2007
Parsing and Syntax I

Overview

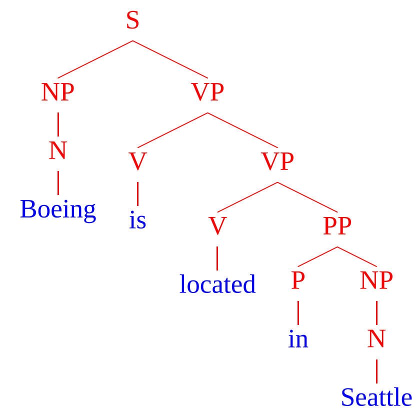
- An introduction to the parsing problem
- Context free grammars
- A brief(!) sketch of the syntax of English
- Examples of ambiguous structures
- PCFGs, their formal properties, and useful algorithms
- Weaknesses of PCFGs

Parsing (Syntactic Structure)

INPUT:

Boeing is located in Seattle.

OUTPUT:



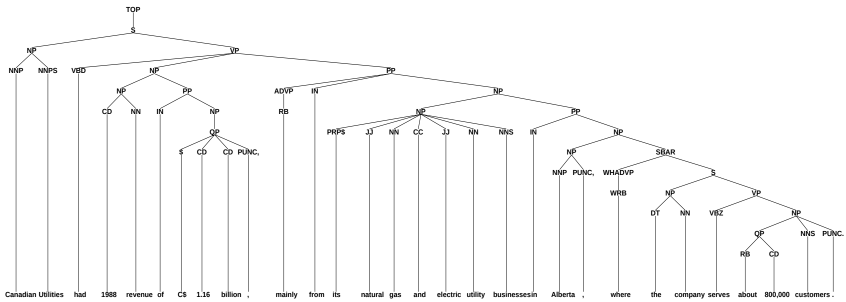
Syntactic Formalisms

- Work in formal syntax goes back to Chomsky's PhD thesis in the 1950s
- Examples of current formalisms: minimalism, lexical functional grammar (LFG), head-driven phrase-structure grammar (HPSG), tree adjoining grammars (TAG), categorial grammars

Data for Parsing Experiments

- Penn WSJ Treebank = 50,000 sentences with associated trees
- Usual set-up: 40,000 training sentences, 2400 test sentences

An example tree:

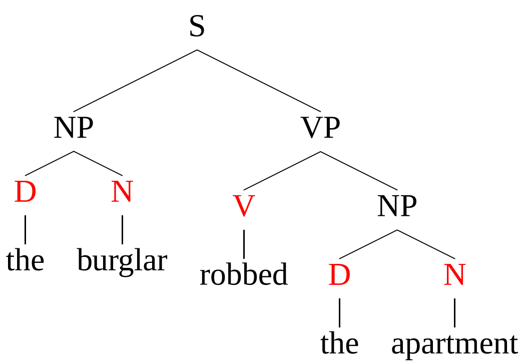


Canadian Utilities had 1988 revenue of C$ 1.16 billion , mainly from its natural gas and electric utility businesses in Alberta , where the company serves about 800,000 customers .

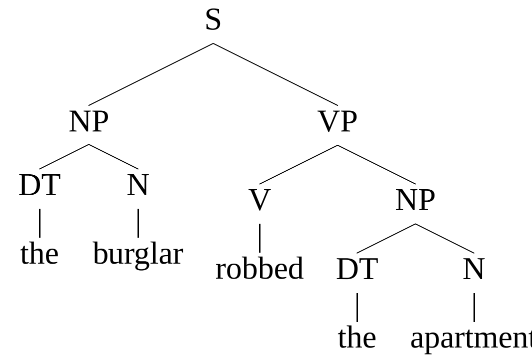
The Information Conveyed by Parse Trees

1) Part of speech for each word

(N = noun, V = verb, D = determiner)



2) Phrases

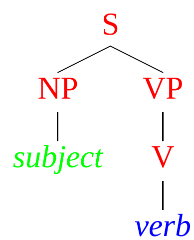


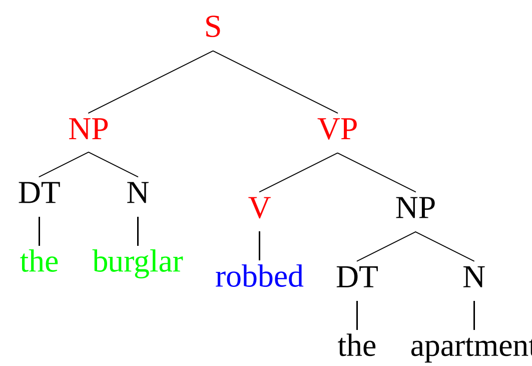
Noun Phrases (NP): “the burglar”, “the apartment”

Verb Phrases (VP): “robbed the apartment”

Sentences (S): “the burglar robbed the apartment”

3) Useful Relationships





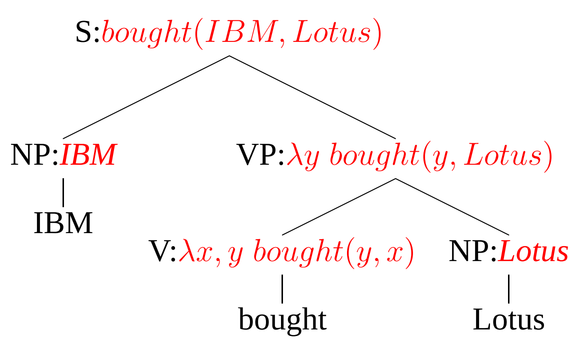
⇒ “the burglar” is the subject of “robbed”

An Example Application: Machine Translation

- English word order is *subject – verb – object*
- Japanese word order is *subject – object – verb*

English:	IBM bought Lotus
Japanese:	*IBM Lotus bought*
English:	Sources said that IBM bought Lotus yesterday
Japanese:	*Sources yesterday IBM Lotus bought that said*

Syntax and Compositional Semantics



- Each syntactic non-terminal now has an associated semantic expression

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Context-Free Grammars

[Hopcroft and Ullman 1979]
A context free grammar $G = (N, \Sigma, R, S)$ where:

- N is a set of non-terminal symbols
- Σ is a set of terminal symbols
- R is a set of rules of the form $X \rightarrow Y_1 Y_2 \ldots Y_n$ for $n \geq 0$, $X \in N$, $Y_i \in (N \cup \Sigma)$
- $S \in N$ is a distinguished start symbol

A Context-Free Grammar for English

N = {S, NP, VP, PP, DT, Vi, Vt, NN, IN}
S = S
Σ = {sleeps, saw, man, woman, telescope, the, with, in}

R =

S	$\Rightarrow$	NP	VP
VP	$\Rightarrow$	Vi	
VP	$\Rightarrow$	Vt	NP
VP	$\Rightarrow$	VP	PP
NP	$\Rightarrow$	DT	NN
NP	$\Rightarrow$	NP	PP
PP	$\Rightarrow$	IN	NP

Vi	$\Rightarrow$	sleeps
Vt	$\Rightarrow$	saw
NN	$\Rightarrow$	man
NN	$\Rightarrow$	woman
NN	$\Rightarrow$	telescope
DT	$\Rightarrow$	the
IN	$\Rightarrow$	with
IN	$\Rightarrow$	in

Note: S=sentence, VP=verb phrase, NP=noun phrase, PP=prepositional phrase, DT=determiner, Vi=intransitive verb, Vt=transitive verb, NN=noun, IN=preposition

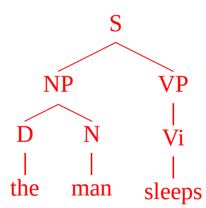
Left-Most Derivations

A left-most derivation is a sequence of strings $s_1 \ldots s_n$, where

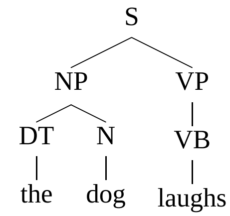
- $s_1 = S$, the start symbol
- $s_n \in \Sigma^*$, i.e. s_n is made up of terminal symbols only
- Each s_i for $i = 2 \ldots n$ is derived from s_{i-1} by picking the left-most non-terminal X in s_{i-1} and replacing it by some β where $X \rightarrow \beta$ is a rule in R

For example: [S], [NP VP], [D N VP], [the N VP], [the man VP], [the man Vi], [the man sleeps]

Representation of a derivation as a tree:



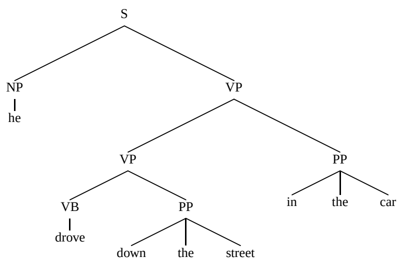
DERIVATION	RULES USED
S	S $\rightarrow$ NP VP
NP VP	NP $\rightarrow$ DT N
DT N VP	DT $\rightarrow$ the
the N VP	N $\rightarrow$ dog
the dog VP	VP $\rightarrow$ VB
the dog VB	VB $\rightarrow$ laughs
the dog laughs	



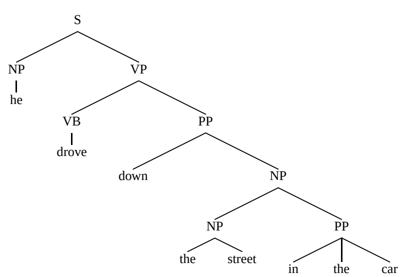
Properties of CFGs

- A CFG defines a set of possible derivations
- A string $s \in \Sigma^*$ is in the *language* defined by the CFG if there is at least one derivation which yields s
- Each string in the language generated by the CFG may have more than one derivation ("ambiguity")

DERIVATION	RULES USED
S	S → NP VP
NP VP	NP → he
he VP	VP → VP PP
he VP PP	VP → VB PP
he VB PP PP	VB→ drove
he drove PP PP	PP→ down the street
he drove down the street PP	PP→ in the car
he drove down the street in the car	



DERIVATION	RULES USED
S	S → NP VP
NP VP	NP → he
he VP	VP → VB PP
he VB PP	VB → drove
he drove PP	PP → down NP
he drove down NP	NP → NP PP
he drove down NP PP	NP → the street
he drove down the street PP	PP → in the car
he drove down the street in the car	

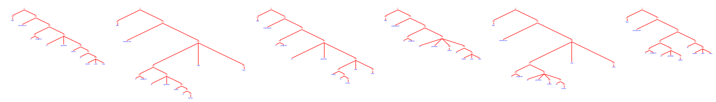


The Problem with Parsing: Ambiguity

INPUT:
She announced a program to promote safety in trucks and vans

⇓

POSSIBLE OUTPUTS:



And there are more...

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The Comprehensive Grammar is an expanded and revised version of a series of grammars

A Brief Overview of English Syntax

Parts of Speech (tags from the Brown corpus):

- Nouns

  NN = singular noun e.g., man, dog, park
  NNS = plural noun e.g., telescopes, houses, buildings
  NNP = proper noun e.g., Smith, Gates, IBM

- Determiners
  DT = determiner e.g., the, a, some, every

- Adjectives
  JJ = adjective e.g., red, green, large, idealistic

A Fragment of a Noun Phrase Grammar

$$
\begin{array}{lcll}
\bar{N} & \Rightarrow & NN & \\
\bar{N} & \Rightarrow & NN & \bar{N} \\
\bar{N} & \Rightarrow & JJ & \bar{N} \\
\bar{N} & \Rightarrow & \bar{N} & \bar{N} \\
NP & \Rightarrow & DT & \bar{N}
\end{array}
$$

$$
\begin{array}{lcl}
NN & \Rightarrow & \text{box} \\
NN & \Rightarrow & \text{car} \\
NN & \Rightarrow & \text{mechanic} \\
NN & \Rightarrow & \text{pigeon} \\
 & & \\
DT & \Rightarrow & \text{the} \\
DT & \Rightarrow & \text{a} \\
 & & \\
JJ & \Rightarrow & \text{fast} \\
JJ & \Rightarrow & \text{metal} \\
JJ & \Rightarrow & \text{idealistic} \\
JJ & \Rightarrow & \text{clay}
\end{array}
$$

Generates:
a box, the box, the metal box, the fast car mechanic, . . .

Prepositions, and Prepositional Phrases

- Prepositions
  IN = preposition   e.g., of, in, out, beside, as

An Extended Grammar

$\bar{N}$	$\Rightarrow$	NN	
$\bar{N}$	$\Rightarrow$	NN	$\bar{N}$
$\bar{N}$	$\Rightarrow$	JJ	$\bar{N}$
$\bar{N}$	$\Rightarrow$	$\bar{N}$	$\bar{N}$
NP	$\Rightarrow$	DT	$\bar{N}$
PP	$\Rightarrow$	IN	NP
$\bar{N}$	$\Rightarrow$	$\bar{N}$	PP

NN	$\Rightarrow$	box
NN	$\Rightarrow$	car
NN	$\Rightarrow$	mechanic
NN	$\Rightarrow$	pigeon
DT	$\Rightarrow$	the
DT	$\Rightarrow$	a

JJ	$\Rightarrow$	fast
JJ	$\Rightarrow$	metal
JJ	$\Rightarrow$	idealistic
JJ	$\Rightarrow$	clay
IN	$\Rightarrow$	in
IN	$\Rightarrow$	under
IN	$\Rightarrow$	of
IN	$\Rightarrow$	on
IN	$\Rightarrow$	with
IN	$\Rightarrow$	as

Generates:
in a box, under the box, the fast car mechanic under the pigeon in the box, . . .

Verbs, Verb Phrases, and Sentences

- Basic Verb Types
  Vi = Intransitive verb   e.g., sleeps, walks, laughs
  Vt = Transitive verb   e.g., sees, saw, likes
  Vd = Ditransitive verb   e.g., gave

- Basic VP Rules
  VP $\rightarrow$ Vi
  VP $\rightarrow$ Vt NP
  VP $\rightarrow$ Vd NP NP

- Basic S Rule
  S $\rightarrow$ NP VP

Examples of VP:
sleeps, walks, likes the mechanic, gave the mechanic the fast car, gave the fast car mechanic the pigeon in the box, . . .

Examples of S:
the man sleeps, the dog walks, the dog likes the mechanic, the dog in the box gave the mechanic the fast car,. . .

PPs Modifying Verb Phrases

A new rule:
VP $\rightarrow$ VP PP

New examples of VP:
sleeps in the car, walks like the mechanic, gave the mechanic the fast car on Tuesday, . . .

Complementizers, and SBARs

- Complementizers
  COMP = complementizer e.g., that

- SBAR
  SBAR $\rightarrow$ COMP S

Examples:
that the man sleeps, that the mechanic saw the dog . . .

More Verbs

- New Verb Types
  V[5] e.g., said, reported
  V[6] e.g., told, informed
  V[7] e.g., bet

- New VP Rules

VP	$\rightarrow$	V[5]	SBAR		
VP	$\rightarrow$	V[6]	NP	SBAR	
VP	$\rightarrow$	V[7]	NP	NP	SBAR

Examples of New VPs:
said that the man sleeps
told the dog that the mechanic likes the pigeon
bet the pigeon $50 that the mechanic owns a fast car

Coordination

- A New Part-of-Speech:
  CC = Coordinator e.g., and, or, but

- New Rules

NP	$\rightarrow$	NP	CC	NP
$\bar{N}$	$\rightarrow$	$\bar{N}$	CC	$\bar{N}$
VP	$\rightarrow$	VP	CC	VP
S	$\rightarrow$	S	CC	S
SBAR	$\rightarrow$	SBAR	CC	SBAR

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Sources of Ambiguity

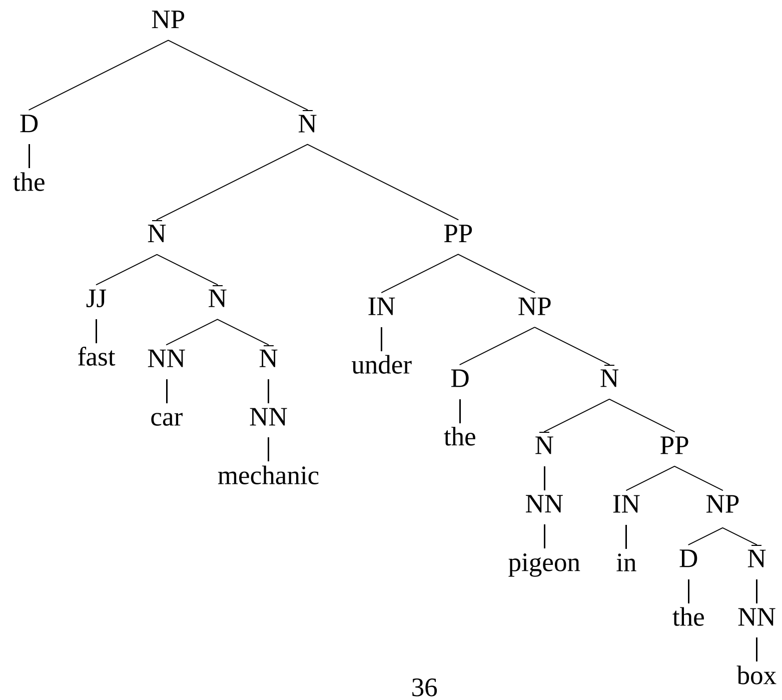
- Part-of-Speech ambiguity

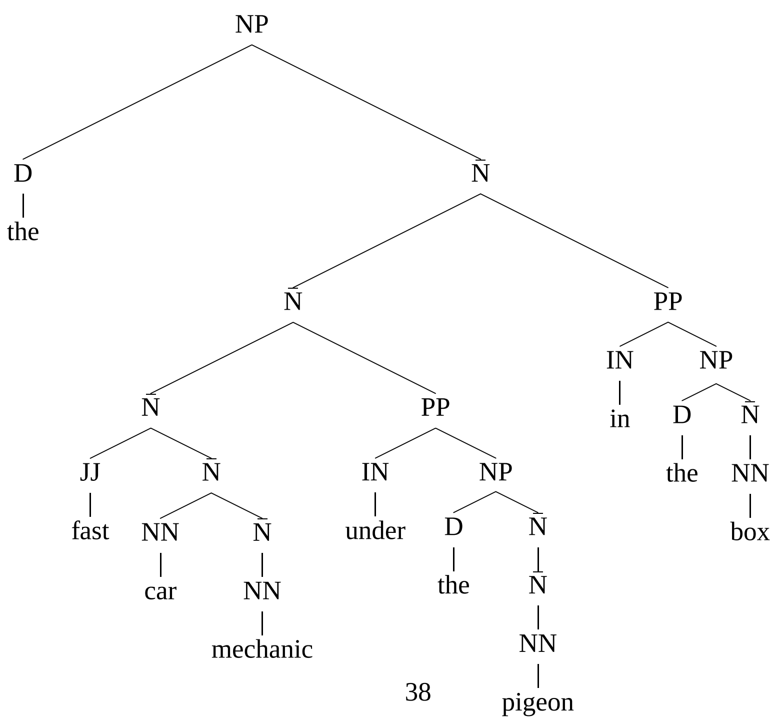
  NNS $\rightarrow$ walks

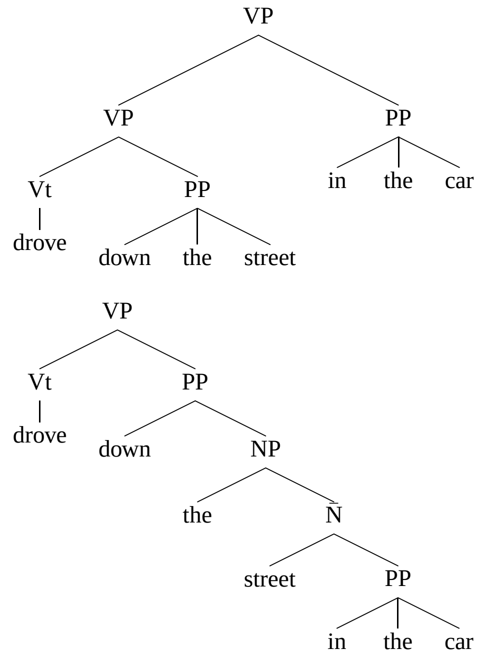
  Vi $\rightarrow$ walks

- Prepositional Phrase Attachment

  the fast car mechanic under the pigeon in the box



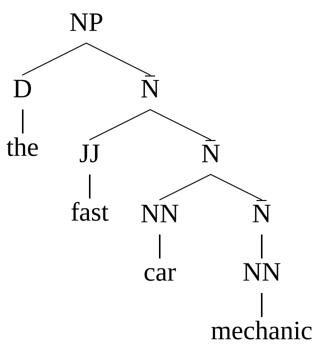


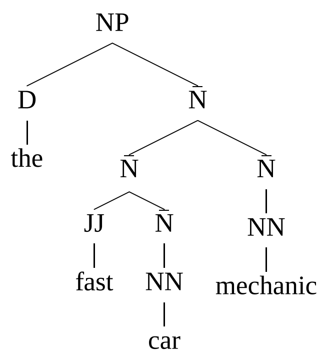


Two analyses for: John was believed to have been shot by Bill

Sources of Ambiguity: Noun Premodifiers

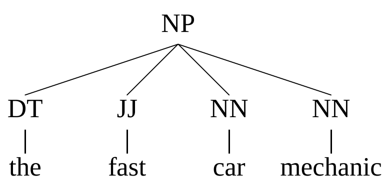
- Noun premodifiers:

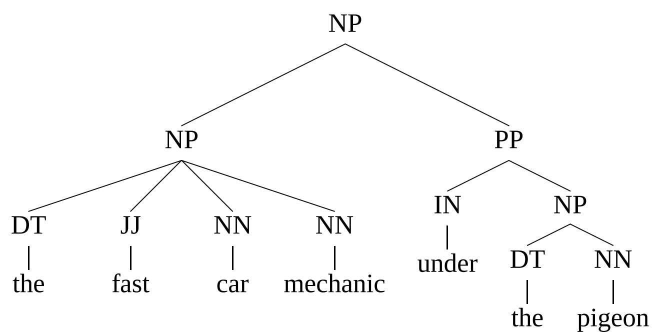




A Funny Thing about the Penn Treebank

Leaves NP premodifier structure flat, or underspecified:





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A Probabilistic Context-Free Grammar (PCFG)

S	⇒	NP	VP	1.0
VP	⇒	Vi		0.4
VP	⇒	Vt	NP	0.4
VP	⇒	VP	PP	0.2
NP	⇒	DT	NN	0.3
NP	⇒	NP	PP	0.7
PP	⇒	P	NP	1.0

Vi	⇒	sleeps	1.0
Vt	⇒	saw	1.0
NN	⇒	man	0.7
NN	⇒	woman	0.2
NN	⇒	telescope	0.1
DT	⇒	the	1.0
IN	⇒	with	0.5
IN	⇒	in	0.5

- Probability of a tree with rules $\alpha_i \rightarrow \beta_i$ is $\prod_i P(\alpha_i \rightarrow \beta_i | \alpha_i)$

DERIVATION	RULES USED	PROBABILITY
S	S $\rightarrow$ NP VP	1.0
NP VP	NP $\rightarrow$ DT N	0.3
DT N VP	DT $\rightarrow$ the	1.0
the N VP	N $\rightarrow$ dog	0.1
the dog VP	VP $\rightarrow$ VB	0.4
the dog VB	VB $\rightarrow$ laughs	0.5
the dog laughs		

TOTAL PROBABILITY = $1.0 \times 0.3 \times 1.0 \times 0.1 \times 0.4 \times 0.5$

Properties of PCFGs

- Assigns a probability to each *left-most derivation*, or parse-tree, allowed by the underlying CFG

- Say we have a sentence S, set of derivations for that sentence is $\mathcal{T}(S)$. Then a PCFG assigns a probability to each member of $\mathcal{T}(S)$. i.e., *we now have a ranking in order of probability*.

- The probability of a string S is

$$\sum_{T \in \mathcal{T}(S)} P(T, S)$$

Deriving a PCFG from a Corpus

- Given a set of example trees, the underlying CFG can simply be **all rules seen in the corpus**

- Maximum Likelihood estimates:

$$P_{ML}(\alpha \rightarrow \beta \mid \alpha) = \frac{\text{Count}(\alpha \rightarrow \beta)}{\text{Count}(\alpha)}$$

  where the counts are taken from a training set of example trees.

- **If the training data is generated by a PCFG**, then as the training data size goes to infinity, the maximum-likelihood PCFG will converge to the same distribution as the "true" PCFG.

PCFGs

[Booth and Thompson 73] showed that a CFG with rule probabilities correctly defines a distribution over the set of derivations provided that:

1. The rule probabilities define conditional distributions over the different ways of rewriting each non-terminal.

2. A technical condition on the rule probabilities ensuring that the probability of the derivation terminating in a finite number of steps is 1. (This condition is not really a practical concern.)

Algorithms for PCFGs

- Given a PCFG and a sentence S, define $\mathcal{T}(S)$ to be the set of trees with S as the yield.

- Given a PCFG and a sentence S, how do we find

$$\arg \max_{T \in \mathcal{T}(S)} P(T, S)$$

- Given a PCFG and a sentence S, how do we find

$$P(S) = \sum_{T \in \mathcal{T}(S)} P(T, S)$$

Chomsky Normal Form

A context free grammar $G = (N, \Sigma, R, S)$ in Chomsky Normal Form is as follows

- N is a set of non-terminal symbols
- Σ is a set of terminal symbols
- R is a set of rules which take one of two forms:
  - $X \rightarrow Y_1 Y_2$ for $X \in N$, and $Y_1, Y_2 \in N$
  - $X \rightarrow Y$ for $X \in N$, and $Y \in \Sigma$
- $S \in N$ is a distinguished start symbol

A Dynamic Programming Algorithm

- Given a PCFG and a sentence S, how do we find

$$\max_{T \in \mathcal{T}(S)} P(T, S)$$

- Notation:

n = number of words in the sentence
N_k for $k = 1 \ldots K$ is k'th non-terminal
$N_1 = S$ (the start symbol)

- Define a dynamic programming table

$\pi[i, j, k]$ = maximum probability of a constituent with non-terminal N_k spanning words $i \ldots j$ inclusive

- Our goal is to calculate $\max_{T \in \mathcal{T}(S)} P(T, S) = \pi[1, n, 1]$

A Dynamic Programming Algorithm

- Base case definition: for all $i = 1 \ldots n$, for $k = 1 \ldots K$

$$\pi[i, i, k] = P(N_k \rightarrow w_i \mid N_k)$$

(note: define $P(N_k \rightarrow w_i \mid N_k) = 0$ if $N_k \rightarrow w_i$ is not in the grammar)

- Recursive definition: for all $i = 1 \ldots n$, $j = (i + 1) \ldots n$, $k = 1 \ldots K$,

$$\pi[i, j, k] = \max_{\substack{i \leq s < j \\ 1 \leq l \leq K \\ 1 \leq m \leq K}} \{P(N_k \rightarrow N_l N_m \mid N_k) \times \pi[i, s, l] \times \pi[s + 1, j, m]\}$$

(note: define $P(N_k \rightarrow N_l N_m \mid N_k) = 0$ if $N_k \rightarrow N_l N_m$ is not in the grammar)

Initialization:

For i = 1 ... n, k = 1 ... K

$\pi[i,i,k] = P(N_k \rightarrow w_i | N_k)$

Main Loop:

For $length = 1 \ldots (n-1)$, $i = 1 \ldots (n - 1ength)$, $k = 1 \ldots K$

$j \leftarrow i + length$

$max \leftarrow 0$

For $s = i \ldots (j-1)$,

For N_l, N_m such that $N_k \rightarrow N_l N_m$ is in the grammar

$prob \leftarrow P(N_k \rightarrow N_l N_m) \times \pi[i,s,l] \times \pi[s+1,j,m]$

If $prob > max$

$max \leftarrow prob$

//Store backpointers which imply the best parse

$Split(i,j,k) = \{s,l,m\}$

$\pi[i,j,k] = max$

A Dynamic Programming Algorithm for the Sum

- Given a PCFG and a sentence S, how do we find

$$\sum_{T \in \mathcal{T}(S)} P(T,S)$$

- Notation:

n = number of words in the sentence

N_k for $k = 1 \ldots K$ is k'th non-terminal

$N_1 = S$ (the start symbol)

- Define a dynamic programming table

$\pi[i,j,k]$ = sum of probability of parses with root label N_k spanning words $i \ldots j$ inclusive

- Our goal is to calculate $\sum_{T \in \mathcal{T}(S)} P(T,S) = \pi[1,n,1]$

A Dynamic Programming Algorithm for the Sum

- Base case definition: for all $i = 1 \ldots n$, for $k = 1 \ldots K$

$$\pi[i,i,k] = P(N_k \rightarrow w_i \mid N_k)$$

(note: define $P(N_k \rightarrow w_i \mid N_k) = 0$ if $N_k \rightarrow w_i$ is not in the grammar)

- Recursive definition: for all $i = 1 \ldots n$, $j = (i+1) \ldots n$, $k = 1 \ldots K$,

$$\pi[i,j,k] = \sum_{\substack{i \le s < j \\ 1 \le l \le K \\ 1 \le m \le K}} \{P(N_k \rightarrow N_l N_m \mid N_k) \times \pi[i,s,l] \times \pi[s+1,j,m]\}$$

(note: define $P(N_k \rightarrow N_l N_m \mid N_k) = 0$ if $N_k \rightarrow N_l N_m$ is not in the grammar)

Initialization:

For i = 1 ... n, k = 1 ... K

$\pi[i,i,k] = P(N_k \rightarrow w_i | N_k)$

Main Loop:

For $length = 1 \ldots (n-1)$, $i = 1 \ldots (n - 1ength)$, $k = 1 \ldots K$

$j \leftarrow i + length$

$sum \leftarrow 0$

For $s = i \ldots (j-1)$,

For N_l, N_m such that $N_k \rightarrow N_l N_m$ is in the grammar

$prob \leftarrow P(N_k \rightarrow N_l N_m) \times \pi[i,s,l] \times \pi[s+1,j,m]$

$sum \leftarrow sum + prob$

$\pi[i,j,k] = sum$

Overview

- An introduction to the parsing problem
- Context free grammars
- A brief(!) sketch of the syntax of English
- Examples of ambiguous structures
- PCFGs, their formal properties, and useful algorithms
- Weaknesses of PCFGs

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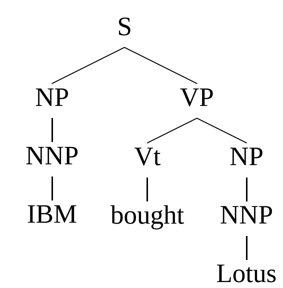
Weaknesses of PCFGs

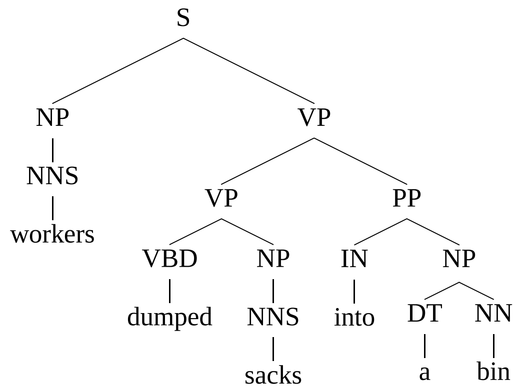
- Lack of sensitivity to lexical information
- Lack of sensitivity to structural frequencies



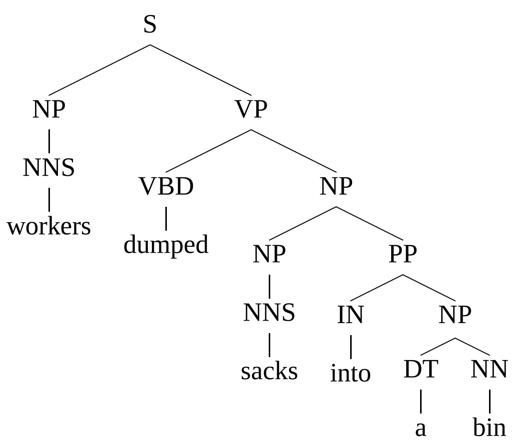
$$\begin{aligned} \text{PROB} = \;& P(\text{S} \rightarrow \text{NP VP} \mid \text{S}) && \times P(\text{NNP} \rightarrow \textit{IBM} \mid \text{NNP}) \\ & \times P(\text{VP} \rightarrow \text{V NP} \mid \text{VP}) && \times P(\text{Vt} \rightarrow \textit{bought} \mid \text{Vt}) \\ & \times P(\text{NP} \rightarrow \text{NNP} \mid \text{NP}) && \times P(\text{NNP} \rightarrow \textit{Lotus} \mid \text{NNP}) \\ & \times P(\text{NP} \rightarrow \text{NNP} \mid \text{NP}) && \end{aligned}$$

Another Case of PP Attachment Ambiguity

(a)



(b)



(a)

Rules
S $\rightarrow$ NP VP
NP $\rightarrow$ NNS
VP $\rightarrow$ VP PP
VP $\rightarrow$ VBD NP
NP $\rightarrow$ NNS
PP $\rightarrow$ IN NP
NP $\rightarrow$ DT NN
NNS $\rightarrow$ workers
VBD $\rightarrow$ dumped
NNS $\rightarrow$ sacks
IN $\rightarrow$ into
DT $\rightarrow$ a
NN $\rightarrow$ bin

(b)

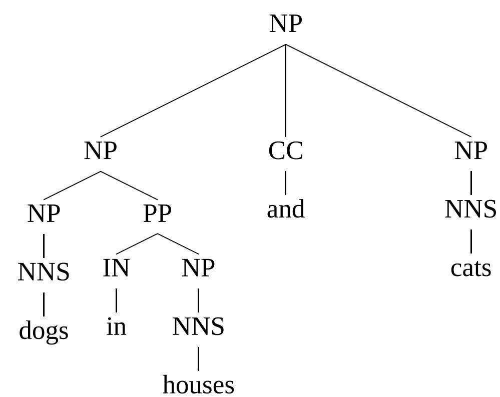
Rules
S $\rightarrow$ NP VP
NP $\rightarrow$ NNS
NP $\rightarrow$ NP PP
VP $\rightarrow$ VBD NP
NP $\rightarrow$ NNS
PP $\rightarrow$ IN NP
NP $\rightarrow$ DT NN
NNS $\rightarrow$ workers
VBD $\rightarrow$ dumped
NNS $\rightarrow$ sacks
IN $\rightarrow$ into
DT $\rightarrow$ a
NN $\rightarrow$ bin

If $P(\text{NP} \rightarrow \text{NP PP} \mid \text{NP}) > P(\text{VP} \rightarrow \text{VP PP} \mid \text{VP})$ then (b) is more probable, else (a) is more probable.

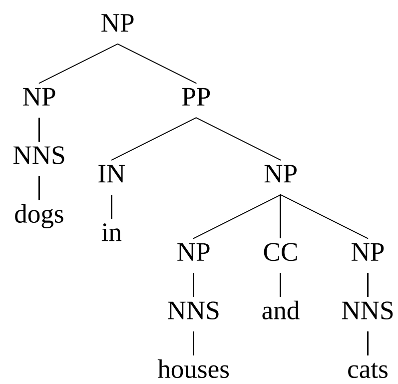
Attachment decision is completely independent of the words

A Case of Coordination Ambiguity

(a)



(b)



(a)

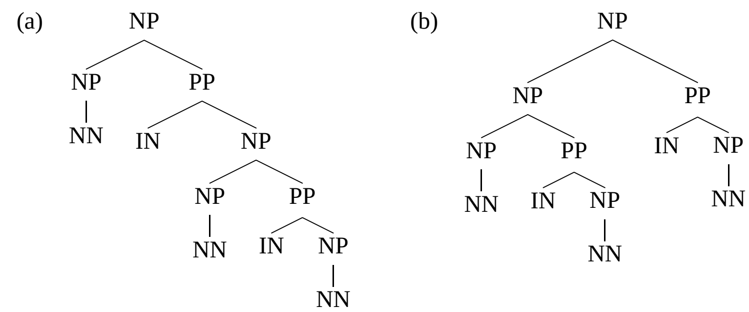
Rules
NP → NP CC NP
NP → NP PP
NP → NNS
PP → IN NP
NP → NNS
NP → NNS
NNS → dogs
IN → in
NNS → houses
CC → and
NNS → cats

(b)

Rules
NP → NP CC NP
NP → NP PP
NP → NNS
PP → IN NP
NP → NNS
NP → NNS
NNS → dogs
IN → in
NNS → houses
CC → and
NNS → cats

Here the two parses have identical rules, and therefore have identical probability under any assignment of PCFG rule probabilities

Structural Preferences: Close Attachment



- Example: president of a company in Africa
- Both parses have the same rules, therefore receive same probability under a PCFG
- “Close attachment” (structure (a)) is twice as likely in Wall Street Journal text.

Structural Preferences: Close Attachment

Previous example: John was believed to have been shot by Bill

Here the low attachment analysis (Bill does the *shooting*) contains same rules as the high attachment analysis (Bill does the *believing*), so the two analyses receive same probability.

References

[Booth and Thompson 73] Booth, T., and Thompson, R. 1973. Applying probability measures to abstract languages. *IEEE Transactions on Computers*, C-22(5), pages 442–450.

[Hopcroft and Ullman 1979] Hopcroft, J. E., and Ullman, J. D. 1979. *Introduction to automata theory, languages, and computation*. Reading, Mass.: Addison–Wesley.