Chapter NLP:V

V. Syntax

Phrase Structure Grammars

Formal Grammars

A formal grammar is defined by a set of rules with terminal and non-terminal symbols.

- Rules transform non-terminal symbols into other terminal or non-terminal symbols.
- Terminal symbols ($\approx$ words) cannot be transformed any further.
- Non-terminals express clusters or generalizations of terminals.

Grammar (Σ, N, S, R)

- Σ An alphabet (i.e., a finite set of terminal symbols).
- N A finite set of non-terminal symbols.
- S A start non-terminal symbol, $S \in N$.
- R A finite set of production rules, $R \subseteq (\Sigma \cup N)^+ \setminus \Sigma^* \times (\Sigma \cup N)^*$.

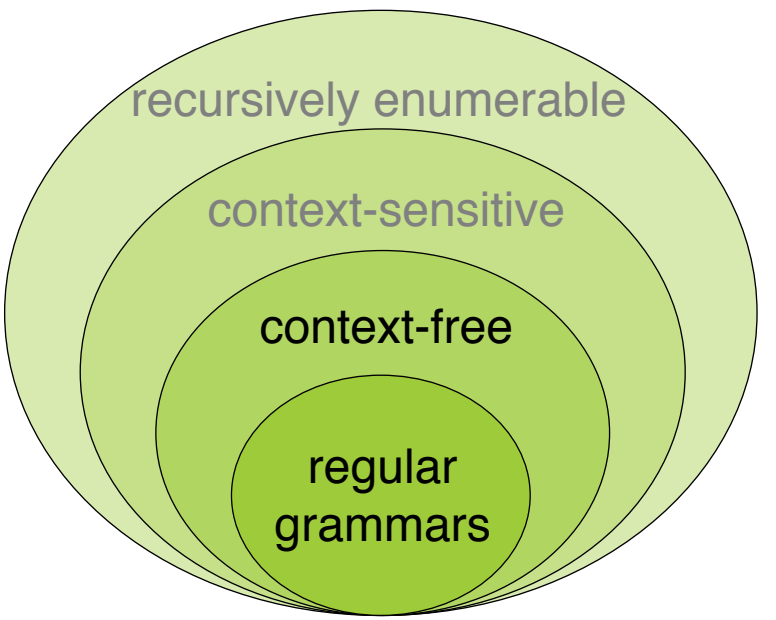
Phrase Structure Grammars

Chomsky Hierarchy

Formal grammars can be ordered in four types:

- Chomsky-0 (recursively enumerable). Any (Σ, N, S, R) as defined.
- Chomsky-1 (context-sensitive). Only rules $U \to V$ with $|U| \leq |V|$.
- Chomsky-2 (context-free). Only rules $U \to V$ with $U \in N$.
- Chomsky-3 (regular). Only rules $U \to V$ with $U \in N$ and $V \in \{\varepsilon, v, vW\}$, $v \in \Sigma$, $W \in N$.

In NLP most commonly used are regular and context-free grammars.



Remarks:

- Context-sensitive grammars allow multiple symbols on the left side (but at least one non-terminal) and multiple symbold on the right side without contraints.
  $S \rightarrow abc/aAbc$, $Ab \rightarrow bA$, $Ac \rightarrow Bbcc$, $bB \rightarrow Bb$, $aB \rightarrow aa/aaA$
- Context-free grammars require a single non-teminal symbol on the left side. For example:
  $N = \{S, X\}, \Sigma = \{a, b\}$, $S \rightarrow ab$, $S \rightarrow aXb$, $X \rightarrow ab$, $X \rightarrow aXb$
- Regular grammars are particularly useful in inferring information when language follows clear sequential patterns (i.e. pattern parsing). Consider our lecture on regular expressions for details.

Phrase Structure Grammars

Context-free grammars (CFG)

A phrase structure grammar is a syntactic structure based on the constituency relation between words.

Phrase structure grammars can be modeled as context-free grammars:

$$(\Sigma,\ S,\ N_{phr} \cup N_{pos},\ R_{phr} \cup R_{pos})$$

- Σ The alphabet.
- S The start symbol.
- N_{phr} A finite set of structural non-terminal symbols. NP, VP, ...
- N_{pos} A finite set of lexical pre-terminal symbols. NN, VB, PRP, ...

  $N_{phr} \cap N_{pos} = \emptyset$
- R_{phr} A finite set of structure production rules. S $\rightarrow$ NP VP, ...

  $U \rightarrow V, U \in N_{phr} \quad V \in (N_{phr} \cup N_{pos})^*$
- R_{pos} A finite set of lexicon production rules. NP $\rightarrow$ DET NN NN, ...

  $U \rightarrow v, U \in N_{pos} \quad v \in \Sigma$

Phrase Structure Grammars

Context-free grammars (CFG)

Some typical (English) phrase structures:

	Structural rule	Example
Clause Structures		
Declarative Clause	S → NP VP	I take the flight tomorrow
Imperative Clause	S → VP	Show me the next train
Yes-no Question	S → *Aux* NP VP	*Do* you get off there?
Noun Phrase Structures		
Determiners	NP → DET NP	the flight
Adjective Phrases	NP → JJ NP	the earliest flight
Gerundive	NP → NP VP	Show me the flights leaving today
Verb Phrase Structures		
Verb Phrase	VP → Verb NP	take the train
Sentential Complement	VP → Verb S	I think I want to take the train
Two Verb Phrases	VP → Verb VP	I want to arrange three flights
Coordinations		
Coordination	NP → NP and NP	the flights and the cost

Phrase Structure Grammars

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Phrase Structure Grammars

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Phrase Structure Grammars

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Coordinations		
Coordination	NP → NP *and* NP	the flights *and* the cost

Phrase Structure Grammars

CFG: Example Grammar

Structural rules		Lexical rules	
s1	S $\rightarrow$ NP VP	l1	N $\rightarrow$ people
s2	VP $\rightarrow$ V NP	l2	| $\rightarrow$ fish
s3	| $\rightarrow$ V NP PP	l3	| $\rightarrow$ tanks
s4	NP $\rightarrow$ NP NP	l4	| $\rightarrow$ rods
s5	| $\rightarrow$ NP PP // binary	l5	V $\rightarrow$ people
s6	| $\rightarrow$ N // unary	l6	| $\rightarrow$ fish
s7	| $\rightarrow$ ε // empty	l7	| $\rightarrow$ tanks
s8	PP $\rightarrow$ P NP	l8	P $\rightarrow$ with

Alternative:

Structural rules	Lexical rules
S $\rightarrow$ NP VP	
NP $\rightarrow$ NP NP | NP PP | N | ε	N $\rightarrow$ people | fish | tanks | rods
VP $\rightarrow$ V NP | V NP PP	V $\rightarrow$ people | fish | tanks
PP $\rightarrow$ P NP	P $\rightarrow$ with

Phrase Structure Grammars

CFG Construction: Treebanks

- A phrase structure grammar consists of many (10k) rules.
- These rules are extracted from corpora with tree-structured expert annotations: treebanks. The most popular Treebanks are:
  1. The *Penn Treebank* (PTB) for constituency trees. [Marcus et al., 1993]
  2. The Universal Dependencies treebank for dependency structures.

Example from the Brown Corpus:

```
((S
   (NP-SBJ (DT That)
     (JJ cold) (, ,)
     (JJ empty) (NN sky) )
   (VP (VBD was)
     (ADJP-PRD (JJ full)
       (PP (IN of)
         (NP (NN fire)
           (CC and)
           (NN light) ))))
   (. .) ))
```

Structural rules		
S	→	NP-SBJ VP
NP-SBJ	→	DT JJ , JJ NN
VP	→	VBD ADJP-PRD
ADJP-PRD	→	JJ PP
PP	→	IN NP
NP	→	NN CC NN

Lexical rules		
NN	→	sky | fire | light
VBD	→	was
JJ	→	cold | empty | full
DT	→	That
IN	→	of
CC	→	and

Phrase Structure Grammars

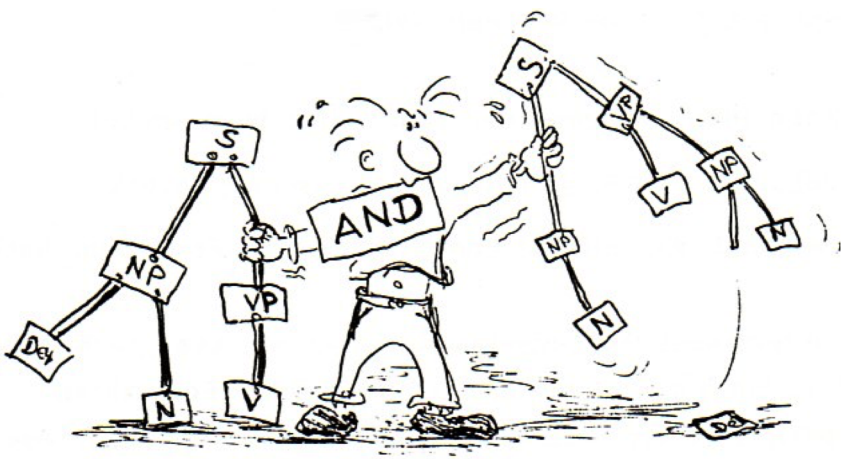
Constituency Parsing

Classical parsing

- Hand-crafted grammar (CFG or more complex), along with a lexicon.
- Usage of grammar-based systems to prove parses from words.
- This scales badly and fails to give high coverage of language.

Example: “Fed raises interest rates 0.5% in effort to control inflation”

- Minimal grammar: 36 parses
- Real-size broad-coverage grammar: Millions of parses



Phrase Structure Grammars

CFG Modifications for Parsing

Parsing with a CFG from a Treebank often yields long, specific, and rare rules:

- Parsing is inefficient.
- Parsing generalizes poorly.
- Syntactic disambiguation is difficult.

Some rules from Penn:

```
NP → DT JJ NN
NP → DT JJ NN NN
NP → DT JJ JJ NN
NP → RB DT JJ NN NN
NP → RB DT JJ JJ NNS
NP → DT NNP NNP NNP NNP JJ NN
NP → DT VBG JJ NNP NNP CC NNP
NP → DT JJ NNS , NNS CC NN NNS NN
NP → NP JJ , JJ “ SBAR ” NNS
```

CFGs are often modified for parsing:

Probabilistic CFG	Extract the likelihood of each rule. Use the most likely rule when parsing.
Chomsky Normal Form	Normalize rules into (equivalent) binary ones.
Lexicalization	Add prior knowledge from a lexicon.
Linearization	Transform trees to sequences.

Phrase Structure Grammars

Probabilistic CFG

A probabilistic context-free grammar (PCFG) is a CFG where each production rule is assigned a probablility.

PCFG (Σ, N, S, R, P)

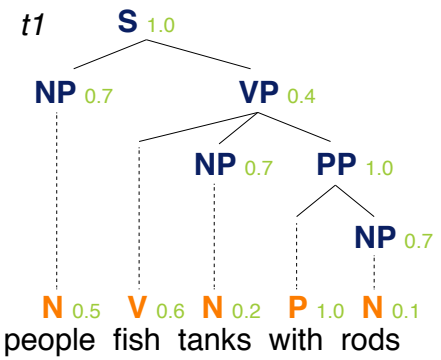
P A probability function $R \to [0, 1]$ from production rules to probabilities, such that

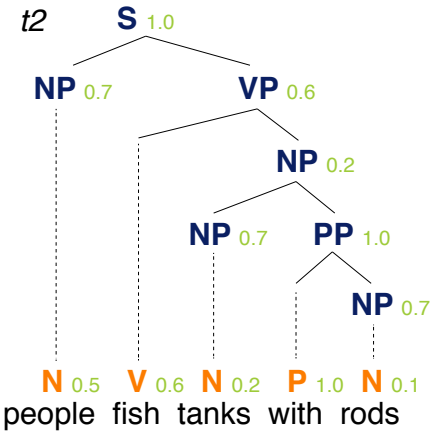
$$\forall U \in N : \sum_{(U \to V) \in R} P(U \to V) = 1$$

- The probability $P(t)$ of a parse tree t is the product of the probabilities of the rules used to generate it.
- The probability $P(s)$ of a clause s is the sum of the probabilities of the parses which yield s.

Phrase Structure Grammars

Probabilistic CFG





Structural rules	P
S → NP VP	1.0
VP → V NP	0.6
VP → V NP PP	0.4
NP → NP NP	0.1
NP → NP PP	0.2
NP → N	0.7
PP → P NP	1.0

Lexical rules	P
N → people	0.5
N → fish	0.2
N → tanks	0.2
N → rods	0.1
V → people	0.1
V → fish	0.6
V → tanks	0.3
P → with	1.0

$$
\begin{aligned}
P(t_1) &= 1.0 \cdot 0.7 \cdot 0.4 \cdot 0.5 \cdot 0.6 \cdot 0.7 \cdot 1.0 \cdot 0.2 \cdot 1.0 \cdot 0.7 \cdot 0.1 \\
&= 0.0008232 \\
P(t_2) &= 1.0 \cdot 0.7 \cdot 0.6 \cdot 0.5 \cdot 0.6 \cdot 0.2 \cdot 0.7 \cdot 1.0 \cdot 0.2 \cdot 1.0 \cdot 0.7 \cdot 0.1 \\
&= 0.00024696 \\
P(s) &= P(t_1) + P(t_2) = 0.0008232 + 0.00024696 \\
&= 0.00107016
\end{aligned}
$$

Phrase Structure Grammars

Chomsky Normal Form

A CFG is in Chomsky Normal Form if all rules in R are in either of the forms:

$U \rightarrow VW$	Two non-terminals on the right side.
$U \rightarrow v$	One terminal symbol on the right side.
$S \rightarrow e$	The empty clause without symbols.

Two grammars are (weakly) equivalent if they generate the same set of strings.

- Grammars can be equivalenty transformed by changing production rules.
- We can transform a CFG to parse it more efficiently.
- The Chomsky Normal Form is a binary branching normalization that is highly useful for parsing.

Phrase Structure Grammars

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Transformation Idea:

1. Split n-ary production rules with helper non-terminals.

   VP $\rightarrow$ NP VP NP $\quad\rightarrow\quad$ VP $\rightarrow$ NP α $\cup$ α $\rightarrow$ VP NP

2. Remove empty rules.

   NP $\rightarrow \epsilon$ $\cup$ VP $\rightarrow$ V NP $\quad\rightarrow\quad$ VP $\rightarrow$ V NP $\cup$ VP $\rightarrow$ V)

3. Replace unary *structure* rules with direct rules.

   NP $\rightarrow$ PP $\cup$ PP $\rightarrow$ P N $\quad\rightarrow\quad$ PP $\rightarrow$ P N $\cup$ NP $\rightarrow$ P N)

Phrase Structure Grammars

Chomsky Normal Form

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$U \rightarrow VW$	Two non-terminals on the right side.
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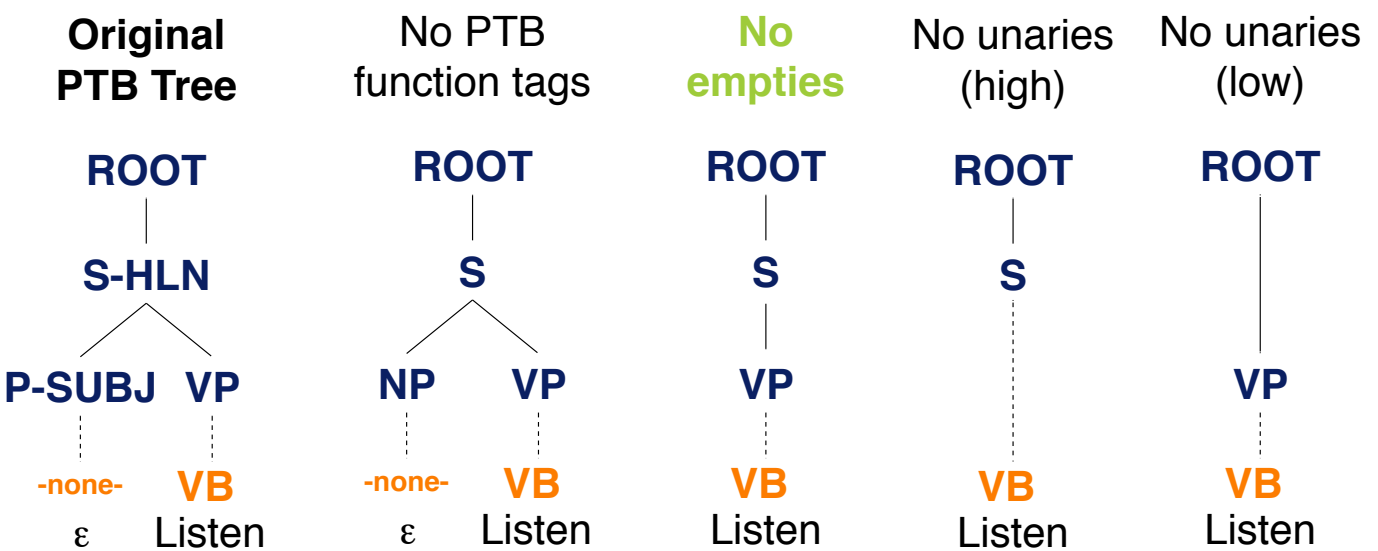
Transformation of Penn (PTB) trees to Chomsky Normal Form (CNF):



Phrase Structure Grammars

CNF Transformation

Signature

- Input. The production rules $R = R_{phr} \cup R_{pos}$ of a CFG.
- Output. The production rules R^* of the normalized version of the CFG.

toChomskyNormalForm(Production rules R)

```
1.    while an empty (U → ε) ∈ R do
2.
3.          // Replace empty rules
4.
5.    while a unary (U → V) ∈ R do
6.
7.
8.          // Replace unary rules
9.
10.
11.   while an n-ary (U → V_1 ... V_n) ∈ R do
12.         // Split n-ary rules with n ≥ 3
13.   return R
```

Phrase Structure Grammars

CNF Transformation: Replace Empty Rules

1. **while** an empty $(U \to \varepsilon) \in R$ **do**
2. $R \leftarrow R \setminus \{U \to \varepsilon\}$
3. **for each** rule $(\mathbf{V} \to \mathbf{V_1} \ldots \mathbf{V_k}\ \mathbf{U}\ \mathbf{W_1} \ldots \mathbf{W_l}) \in R$ **do** // $k, l \geq 0$
4. $R \leftarrow R \cup \{V \to V_1 \ldots V_k\ W_1 \ldots W_l\}$

Structural rules R^{old}	**Lexical rules**
S → NP VP	
VP → V NP | V NP PP	V → people | fish | tanks
NP → NP NP | NP PP | N | ~~NP → ε~~	N → people | fish | tanks | rods
PP → P NP	P → with

Structural rules $R^{\text{no empties}}$	**Lexical rules**
S → **NP VP** | VP	
VP → **V NP** | V | **V NP PP** | V PP	V → people | fish | tanks
NP → **NP NP** | NP | **NP PP** | PP | N	N → people | fish | tanks | rods
PP → **P NP** | P	P → with

Phrase Structure Grammars

CNF Transformation: Replace Unary Rules (1)

5. **while** a unary $(U \to \mathbf{V}) \in R$ **do**
6. $R \leftarrow R \setminus \{U \to \mathbf{V}\}$
7. **if** $U \neq V$ **then**
8. **for each** $(\mathbf{V} \to \mathbf{V_1} \ldots \mathbf{V_k}) \in R$ **do** $R \leftarrow R \cup \{U \to V_1 \ldots V_k\}$
9. **if not** $(W \to V_1 \ldots V_k \; V W_1 \ldots W_l) \in R$ **then**
10. **for each** $(V \to V_1 \ldots V_k) \in R$ **do** $R \leftarrow R \setminus \{V \to V_1 \ldots V_k\}$

Structural rules R$^{\text{no empties}}$	**Lexical rules**
S → NP VP | ~~VP~~	
VP → V NP | V | V NP PP | V PP	V → people | fish | tanks
NP → NP NP | NP | NP PP | PP | N	N → people | fish | tanks | rods
PP → P NP | P	P → with

Structural rules R$^{\text{no unaries 1}}$	**Lexical rules**
S → NP VP | V NP | V | V NP PP | V PP	
VP → V NP | V | V NP PP | V PP	V → people | fish | tanks
NP → NP NP | NP | NP PP | PP | N	N → people | fish | tanks | rods
PP → P NP | P	P → with

Phrase Structure Grammars

CNF Transformation: Replace Unary Rules (2)

5. **while** a unary $(U \to \mathbf{V}) \in R$ **do**
6. $R \leftarrow R \setminus \{U \to \mathbf{V}\}$
7. **if** $U \neq V$ **then**
8. **for each** $(\mathbf{V} \to \mathbf{V_1} \ldots \mathbf{V_k}) \in R$ **do** $R \leftarrow R \cup \{U \to V_1 \ldots V_k\}$
9. **if not** $(W \to V_1 \ldots V_k \; V W_1 \ldots W_l) \in R$ **then**
10. **for each** $(V \to V_1 \ldots V_k) \in R$ **do** $R \leftarrow R \setminus \{V \to V_1 \ldots V_k\}$

Structural rules $R^{\text{no unaries 1}}$	**Lexical rules**
S → NP VP | V NP | V | V NP PP | V PP	
VP → V NP | ~~V~~ | V NP PP | V PP	V → people | fish | tanks
NP → NP NP | NP | NP PP | PP | N	N → people | fish | tanks | rods
PP → P NP | P	P → with

Structural rules $R^{\text{no unaries 2}}$	**Lexical rules**
S → NP VP | V NP | V | V NP PP | V PP	
VP → V NP | V NP PP | V PP	**V → people | fish | tanks**
	VP → people | fish | tanks
NP → NP NP | NP | NP PP | PP | N	N → people | fish | tanks | rods
PP → P NP | P	P → with

Phrase Structure Grammars

CNF Transformation: Replace Unary Rules (3-7)

5. **while** a unary $(U \to \mathbf{V}) \in R$ **do**
6. $R \leftarrow R \setminus \{U \to \mathbf{V}\}$
7. **if** $U \neq V$ **then**
8. **for each** $(\mathbf{V} \to \mathbf{V_1} \ldots \mathbf{V_k}) \in R$ **do** $R \leftarrow R \cup \{U \to V_1 \ldots V_k\}$
9. **if not** $(W \to V_1 \ldots V_k \; V W_1 \ldots W_l) \in R$ **then**
10. **for each** $(V \to V_1 \ldots V_k) \in R$ **do** $R \leftarrow R \setminus \{V \to V_1 \ldots V_k\}$

Structural rules R$^{\text{no unaries 2}}$	**Lexical rules**
S → NP VP | V NP | ~~V~~ | V NP PP | V PP	
VP → V NP | V NP PP | V PP	V → people | fish | tanks
	VP → people | fish | tanks
NP → NP NP | ~~NP~~ | NP PP | ~~PP~~ | ~~N~~	N → people | fish | tanks | rods
PP → P NP | ~~P~~	P → with

Structural rules R$^{\text{no unaries}}$	**Lexical rules**
S → NP VP | V NP | V NP PP | V PP	S → people | fish | tanks
VP → V NP | V NP PP | V PP	V → people | fish | tanks
	VP → people | fish | tanks
NP → NP NP | NP PP | P NP	N → people | fish | tanks | rods
PP → P NP	P → with
	NP → people | fish | tanks | rods | with
	PP → with

Phrase Structure Grammars

CNF Transformation: Split n-ary rules with $n \geq 3$

11. **while** an n-ary $(U \to V_1 \dots V_n) \in R$ **do** // $n \geq 3$
12. $R \leftarrow (R \setminus \{U \to \mathbf{V_1}, V_2, \dots V_n\}) \cup \{U \to \mathbf{V_1}\ \mathbf{U\_V_1},\ \mathbf{U\_V_1} \to V_2 \dots V_n\}$

Structural rules $R^{\text{no unaries}}$	**Lexical rules**
S → NP VP | V NP | ~~V NP PP~~ | V PP	S → people | fish | tanks
VP → V NP | ~~V NP PP~~ | V PP	V → people | fish | tanks
	VP → people | fish | tanks
NP → NP NP | NP PP | P NP	N → people | fish | tanks | rods
PP → P NP	P → with
	NP → people | fish | tanks | rods | with
	PP → with

Structural rules R^{CNF}	**Lexical rules**
S → NP VP | V NP | **V S_V** | V PP	S → people | fish | tanks
S_V → NP PP	
VP → V NP | **V VP_V** | V PP	V → people | fish | tanks
VP_V → NP PP	VP → people | fish | tanks
NP → NP NP | NP PP | P NP	N → people | fish | tanks | rods
PP → P NP	P → with
	NP → people | fish | tanks | rods | with
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Phrase Structure Grammars

Chomsky Normal Form Transformation: Pseudocode

Signature

- Input. The production rules $R = R_{phr} \cup R_{pos}$ of a CFG.
- Output. The production rules R^* of the normalized version of the CFG.

toChomskyNormalForm(Production rules R)

1. **while** an empty $(U \to \varepsilon) \in R$ **do**
2. $R \leftarrow R \setminus \{U \to \varepsilon\}$
3. **for each** rule $(V \to V_1 \dots V_k\, U\, W_1 \dots W_l) \in R$ **do** // $k, l \geq 0$
4. $R \leftarrow R \cup \{V \to V_1 \dots V_k\ W_1 \dots W_l\}$
5. **while** a unary $(U \to V) \in R$ **do**
6. $R \leftarrow R \setminus \{U \to V\}$
7. **if** $U \neq V$ **then**
8. **for each** $(V \to V_1 \dots V_k) \in R$ **do** $R \leftarrow R \cup \{U \to V_1 \dots V_k\}$
9. **if not** $(W \to V_1 \dots V_k\ V\, W_1 \dots W_l) \in R$ **then**
10. **for each** $(V \to V_1 \dots V_k) \in R$ **do** $R \leftarrow R \setminus \{V \to V_1 \dots V_k\}$
11. **while** an n-ary $(U \to V_1 \dots V_n) \in R$ **do** // $n \geq 3$
12. $R \leftarrow (R \setminus \{U \to V_1 \dots V_n\}) \cup \{U \to V_1\, U\_V_1,\ U\_V_1 \to V_2 \dots V_n\}$
13. **return** R

Remarks:

- The original algorithm presented by Chomsky has 5 steps: START, TERM, BIN, DEL, and UNIT.
- `toChomskyNormalForm` only uses DEL, UNIT, and BIN in that order. The order can be changed, but DEl must come before UNIT.
- START eliminated `S` on the RHS, which should not occur in natural language.
- TERM splits rules with mixed terminals and non-terminals. We assume that the initial Grammar was extraced without such constructs.

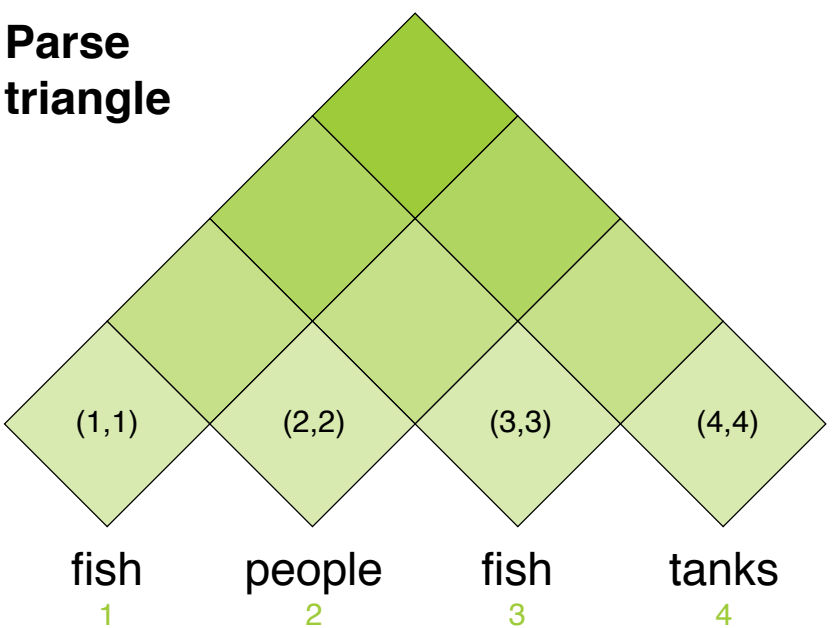
Phrase Structure Grammars

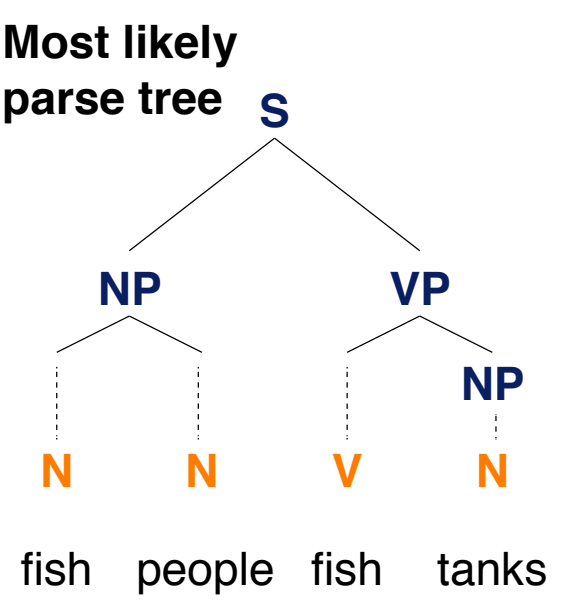
Cocke-Kasami-Younger (CKY) Parsing

PCFGs in CNF can be parsed via dynamic programming:

- CKY finds the most likely parse tree from the PCFGs probabilities.
- With a CFG in CNF, CKY parses in cubic time and quadratic space.

  With respect to the length of the sentence and the number of non-terminals.





Parsing based on a PCFG

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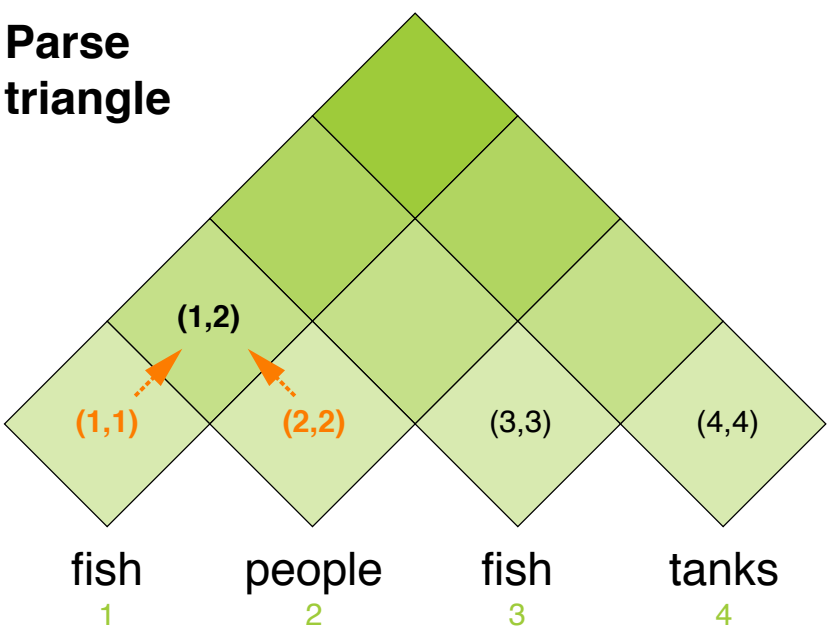
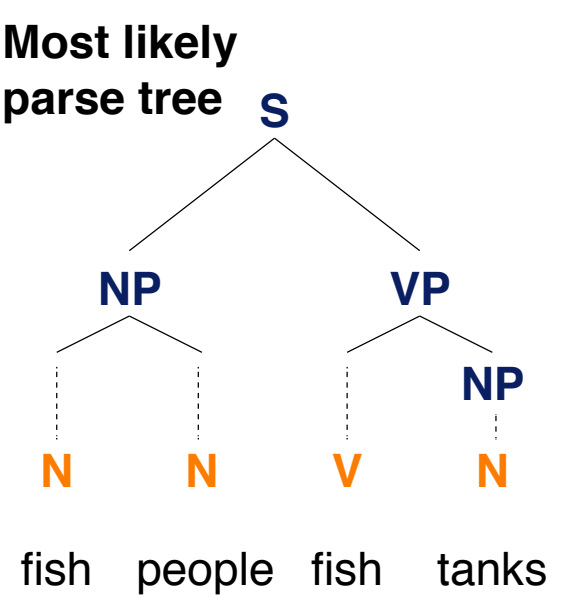
  With respect to the length of the sentence and the number of non-terminals.





Parsing based on a PCFG

Cocke-Kasami-Younger (CKY) Parsing

PCFGs in CNF can be parsed via dynamic programming:

- CKY finds the most likely parse tree from the PCFGs probabilities.
- With a CFG in CNF, CKY parses in cubic time and quadratic space.

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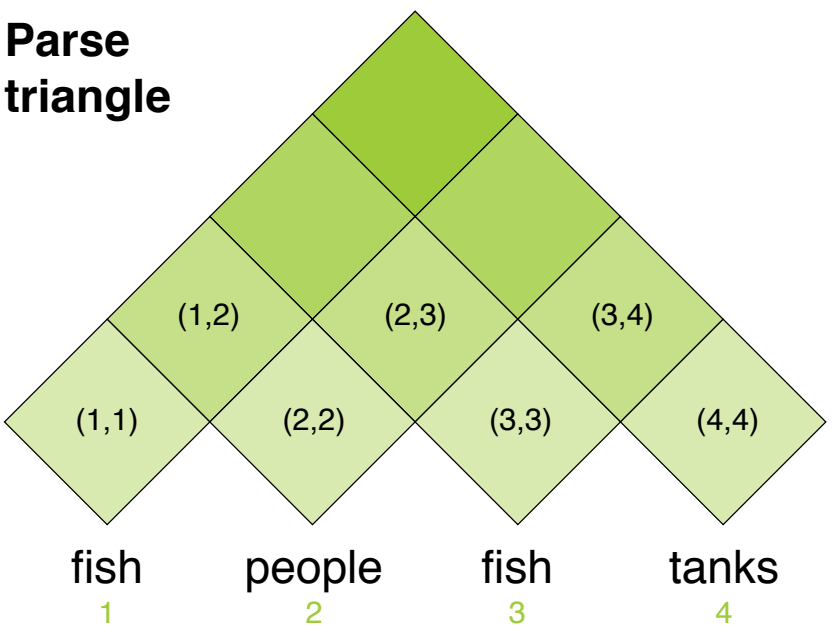
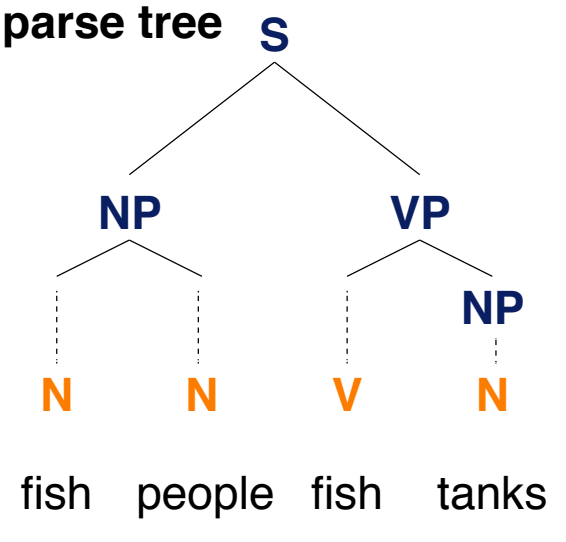
Parse triangle



Most likely parse tree



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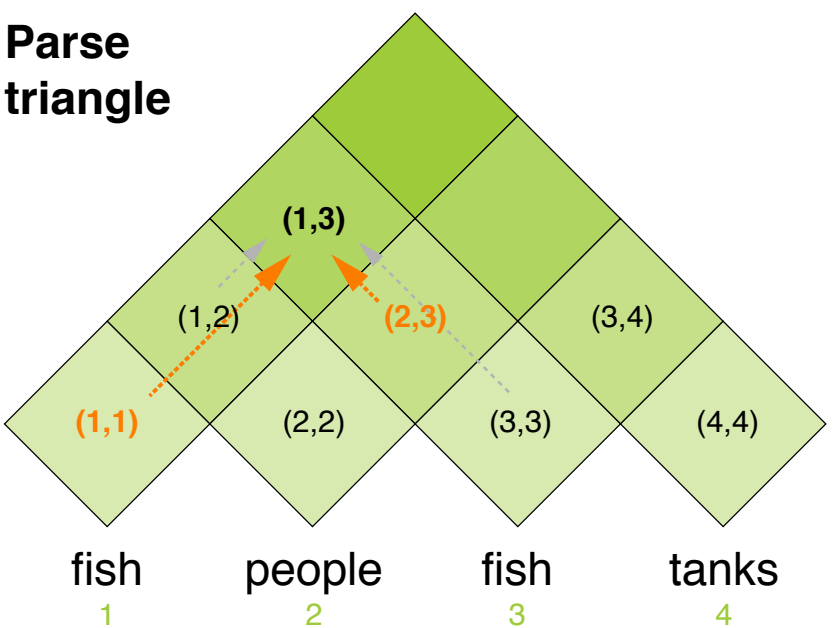

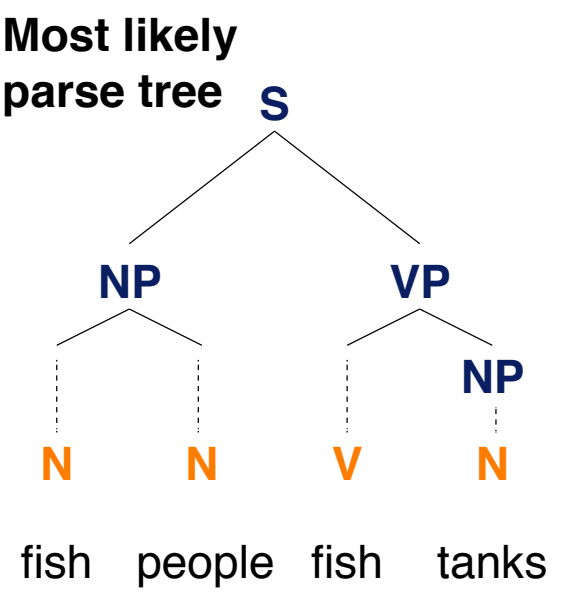

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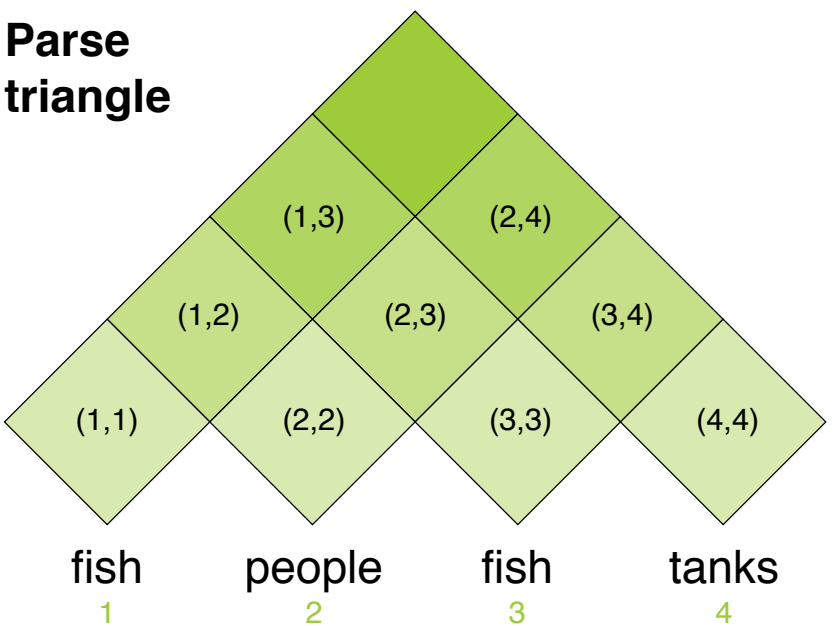

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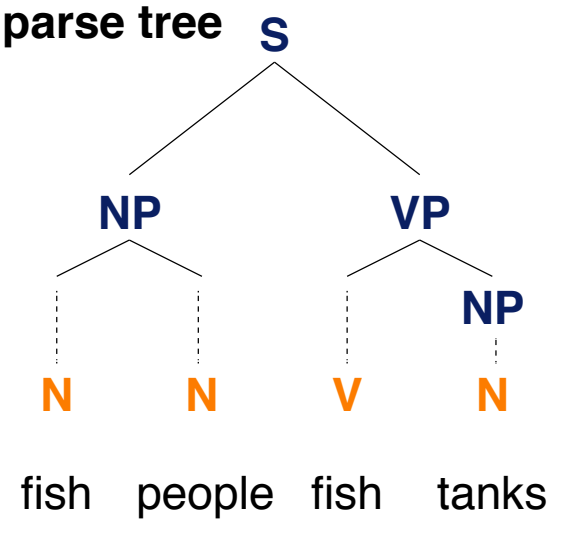

Parsing based on a PCFG

Cocke-Kasami-Younger (CKY) Parsing

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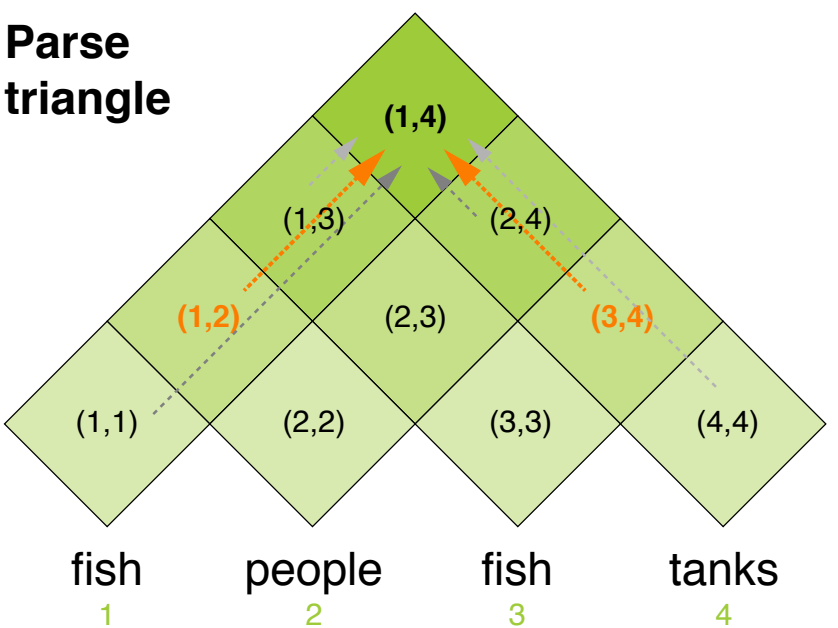
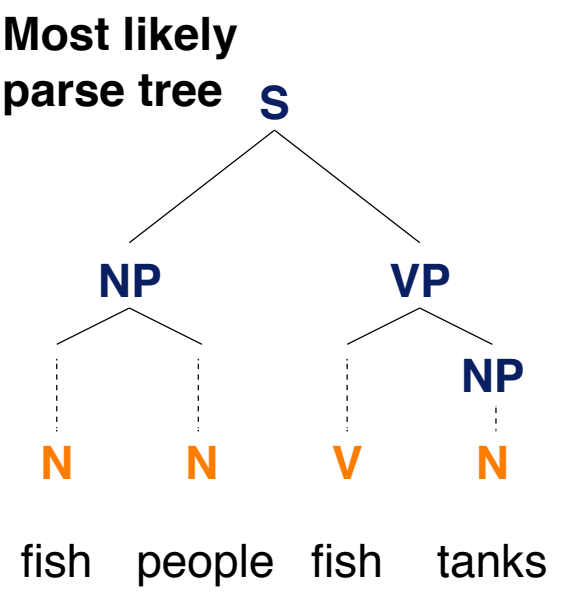
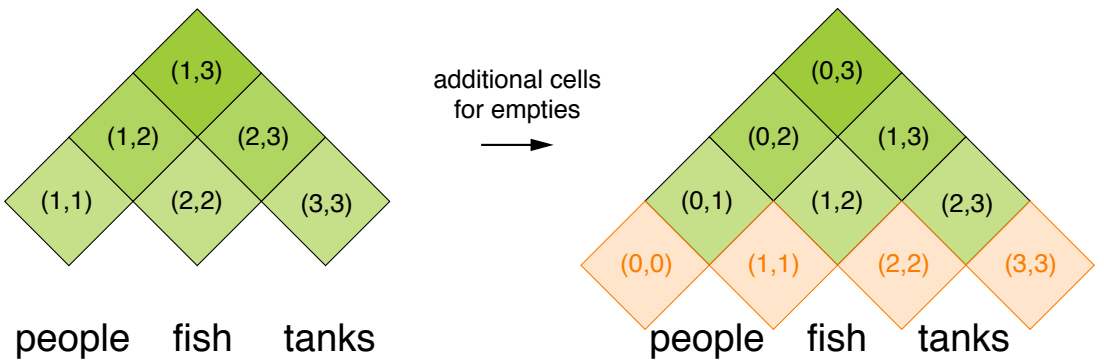




Remarks:

- The binarization from the CNF is crucial for cubic time.
- CKY can be extended to include Unaries and Empties without increasaing time comlexity. This just makes the algorithm more messy:



Phrase Structure Grammars

CKY Parsing: Pseudo Code 1/2

Signature

- Input. A sentence (represented by a list of tokens), a binarized PCFG.
- Output. The most likely parse tree of the sentence.

extendedCKYParsing(List<Token> tokens, PCFG (Σ, N, S, R, P))

```
1.     double [][][] probs ← new double[#tokens][#tokens][#N]
2.     for int i ← 1 to #tokens do // Lexical rules (and unaries)
3.         for each U ∈ N do
4.             if (U→tokens[i]) ∈ P then
5.                 probs[i][i][U] ← P(U→tokens[i])
6.
7.
8.
9.
10.        // ...  handle unaries...
11.
12.
13.
14.
15.    // ...  continued on next slide...
```

Parsing based on a PCFG

CKY Parsing: Pseudo Code 1/2

Signature

- Input. A sentence (represented by a list of tokens), a binarized PCFG.
- Output. The most likely parse tree of the sentence.

extendedCKYParsing(List<Token> tokens, PCFG (Σ, N, S, R, P))

```
1.    double [][][] probs ← new double[#tokens][#tokens][#N]
2.    for int i ← 1 to #tokens do // Lexical rules (and unaries)
3.       for each U ∈ N do
4.          if (U→tokens[i]) ∈ P then
5.             probs[i][i][U] ← P(U→tokens[i])
6.       boolean added ← 'true' // As of here:  Handle unaries
7.       while added = 'true' do
8.          added ← 'false'
9.          for each U,V ∈ N do
10.            if probs[i][i][V]>0 and (U → V) ∈ P then
11.               double prob ← P(U → V) · probs[i][i][V]
12.               if prob > probs[i][i][U] then
13.                  probs[i][i][U] ← prob
14.                  added ← 'true'
15.   // ...  continued on next slide...
```

Phrase Structure Grammars

CKY Parsing: Pseudo Code 2/2

```
        // ...  lines 1–14 on previous slide...
15.     for int length ← 2 to #tokens do // Structural rules
16.         for int beg ← 1 to #tokens - length + 1 do
17.             int end ← beg + length - 1
18.             for int split ← beg to end-1 do
19.
20.
                    // ...
21.
22.
23.
24.
25.
26.             // ...  handle unaries...
27.
28.
29.
30.
31.     return buildTree(probs) // Reconstruct tree from triangle
```

Phrase Structure Grammars

CKY Parsing: Pseudo Code 2/2

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21.                     int prob ← probs[beg][split][V] ·
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22.                     if prob > probs[beg][end][U] then
23.                         probs[beg][end][U] ← prob
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Phrase Structure Grammars

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21.           if prob > probs[beg][end][U] then
22.             probs[beg][end][U] ← prob
23.       boolean added ← 'true' // As of here:  Handle unaries
24.       while added do
25.         added ← 'false'
26.         for U,V ∈ N do
27.           prob = P(U → V) · probs[beg][end][V];
28.           if prob > probs[beg][end][U] then
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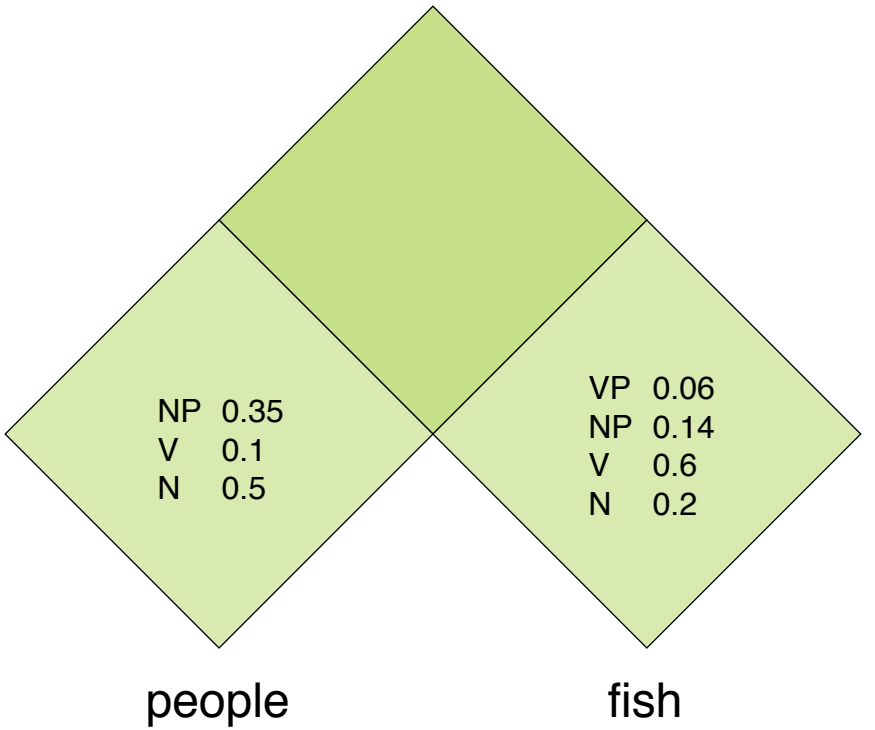
Phrase Structure Grammars

CKY Parsing: Example

A binarized PCFG

Structural rules		
s1	S → NP VP	0.9
s1'	S → VP	0.1
s2	VP → V NP	0.5
s2'	VP → V	0.1
s3'	VP → V VP_V	0.3
s3"	VP → V PP	0.1
s3"'	VP_V → NP PP	1.0
s4	NP → NP NP	0.1
s5	NP → NP PP	0.2
s6	NP → N	0.7
s7	PP → P NP	1.0



Filling cells

- Compute probabilities for each cell.
- Keep only highest for each left side.

Phrase Structure Grammars

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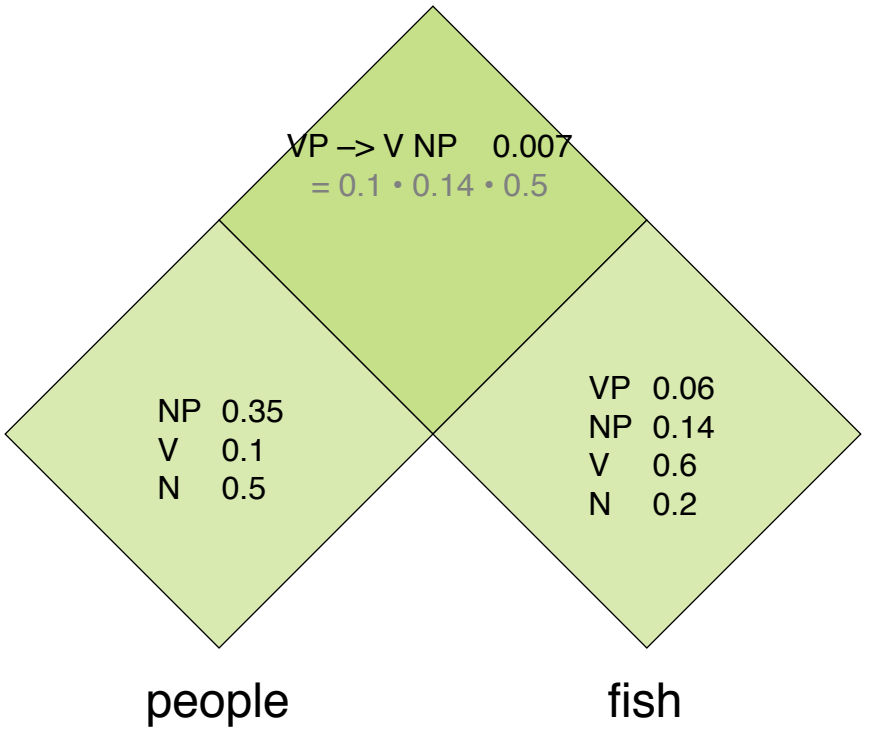

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Phrase Structure Grammars

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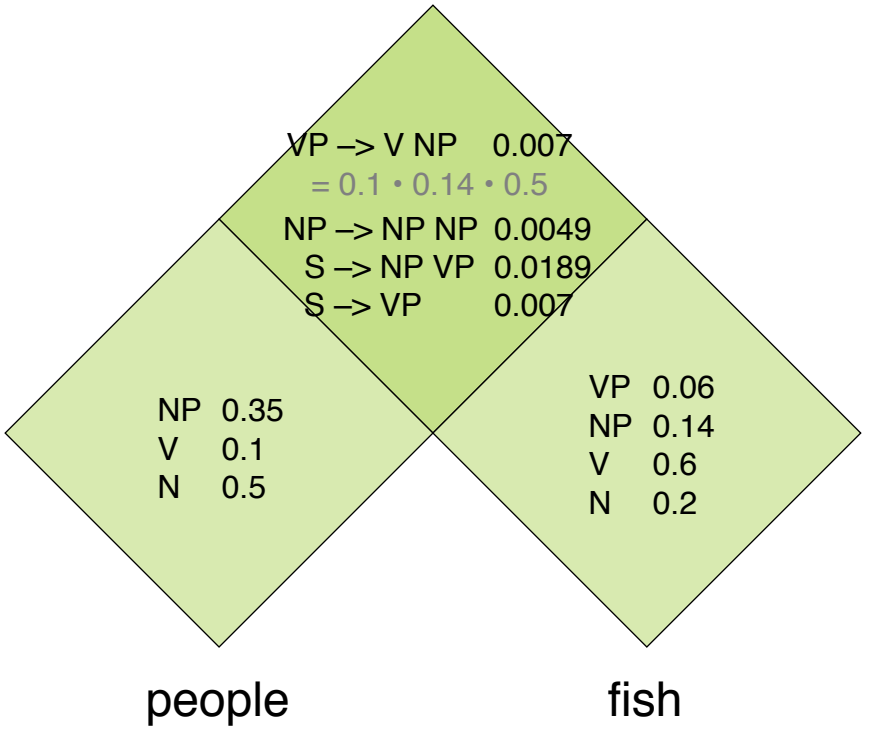

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Phrase Structure Grammars

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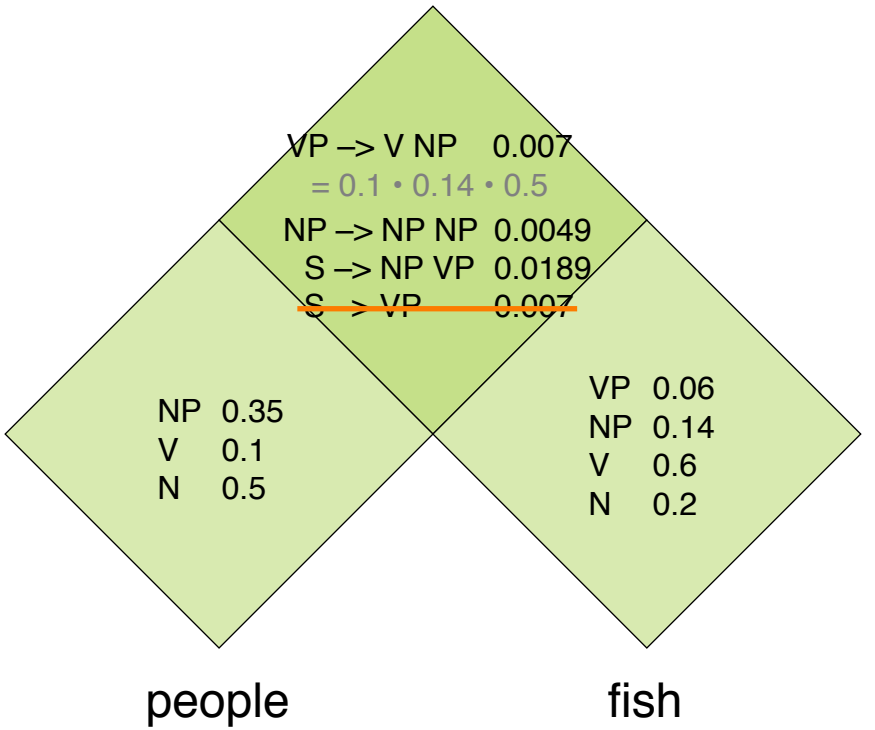


Filling cells

- Compute probabilities for each cell.
- Keep only highest for each left side.

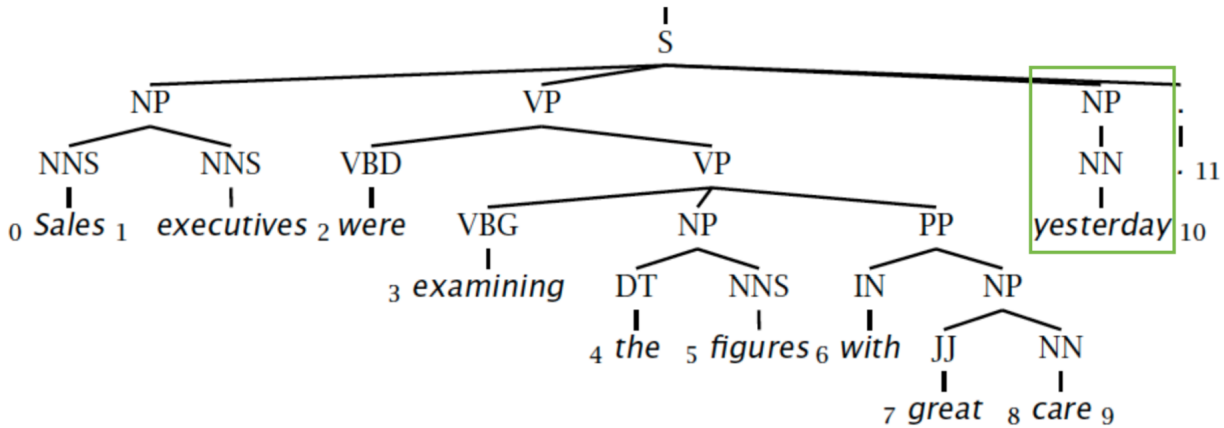
Remarks:

- CKY complexity of pseudo code part 1 is $\mathcal{O}(n \cdot |N|^2)$
  - $\mathcal{O}(n)$ times for-loop in lines 1–14, $n = \#$ tokens.
  - $\mathcal{O}(|N|)$ times for-loop in lines 3–5.
  - $\mathcal{O}(|N|^2)$ times while-loop in lines 7–14.
- CKY complexity of pseudo code part 2 is $\mathcal{O}(n^3 \cdot |N|^3)$
  - $\mathcal{O}(n)$ times for-loop in lines 15–30.
  - $\mathcal{O}(n)$ times for-loop in lines 16–30.
  - $\mathcal{O}(n)$ times for-loop in lines 18–22.
  - $\mathcal{O}(|N|^3)$ times for-loop in lines 19–22.
  - $\mathcal{O}(|N|^2)$ times while-loop in lines 24–30.
  - $\mathcal{O}(n^2)$ for building the tree in line 31.
- Extended CKY parsing has a runtime of $\mathcal{O}(n^3 \cdot |N|^3)$.

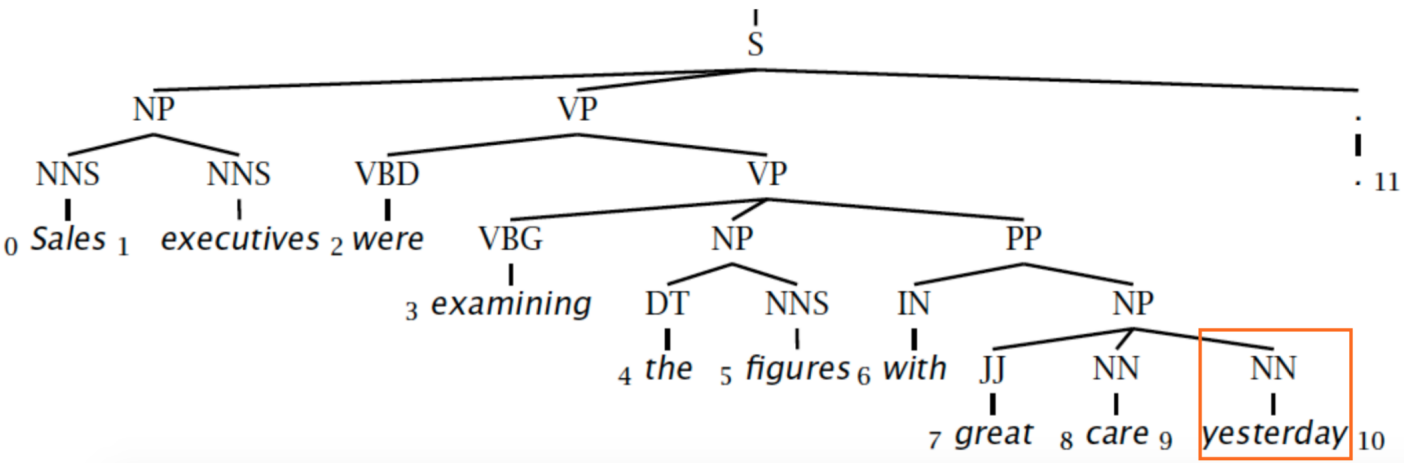
Remarks:

- CKY Parsing: Evaluation of Effectiveness

Gold standard brackets: **S-(0:11)**, **NP-(0:2)**, VP-(2:9), VP-(3:9), **NP-(4:6)**, PP-(6-9), NP-(7,9), NP-(9:10)



Candidate brackets: **S-(0:11)**, **NP-(0:2)**, VP-(2:10), VP-(3:10), **NP-(4:6)**, PP-(6-10), NP-(7,10)



Remarks:

- CKY Parsing: Evaluation of Effectiveness (continued)

8 gold standard brackets
S-(0:11), NP-(0:2), VP-(2:9), VP-(3:9), NP-(4:6), PP-(6:9), NP-(7,9), NP-(9:10)

7 candidate brackets
S-(0:11), NP-(0:2), VP-(2:10), VP-(3:10), NP-(4:6), PP-(6:10), NP-(7,10)

Effectiveness in the example

- Labeled precision (LP). $0.429 = 3 / 7$
- Labeled recall (LR). $0.375 = 3 / 8$
- Labeled F_1-score. $0.400 = 2 \cdot \text{LP} \cdot \text{LR} / (\text{LP} + \text{LR})$
- POS tagging accuracy. $1.000 = 11 / 11$

Effectiveness of CKY in general [Charniak, 1997]

- Labeled F_1 $\sim$0.73 when trained and tested on Penn Treebank.
- CKY is robust (i.e., usually parses everything, but returns tiny probabilities).

Phrase Structure Grammars

Lexicalization

Problem: Probabilistic CFGs assume that the syntax is independent from the terminal symbols.

- PCFGs use production rules for parsing and parse tree probabilities for syntactic disambiguation.
- Information from the words is lost.
- Extending PCFGs by adding contraints from a lexicon is called lexicalization.

There are several PSG formalisms with varying degree of lexicalization:

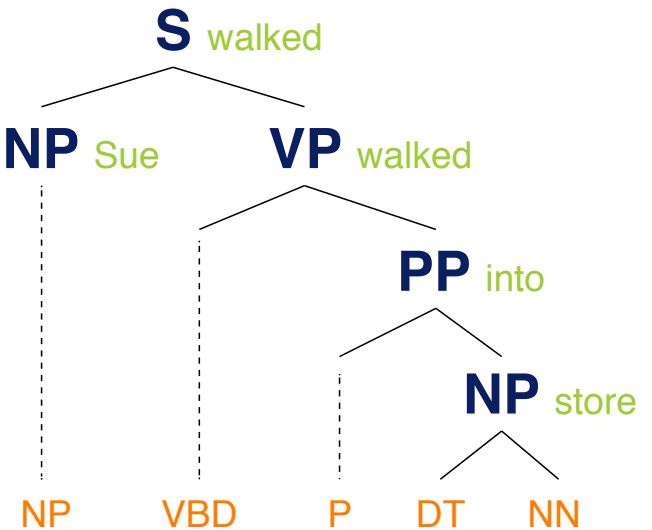
- Lexical-Function Grammar [Bresnan, 1982]
- Head-driven Phrase Structure Grammar [Pollard and Sag, 1994]
- Tree-Adjoining Grammar [Joshi, 1985]
- Combinatory Categorical Grammar
- . . .

Phrase Structure Grammars

Lexicalized PCFG parsing [Collins, 1999]

Idea: The head word of a phrase gives a good representation of the phrase's structure and meaning.

$$
\begin{aligned}
P(\texttt{VP} \rightarrow \texttt{VBD PP}) &= 0.00151 \\
P(\texttt{VP} \rightarrow \texttt{VBD PP} \mid \text{said}) &= 0.00001 \\
P(\texttt{VP} \rightarrow \texttt{VBD PP} \mid \text{gave}) &= 0.01980 \\
P(\texttt{VP} \rightarrow \texttt{VBD PP} \mid \text{walked}) &= 0.02730
\end{aligned}
$$



Phrase Structure Grammars

Unlexicalization [Klein and Manning, 2003]

Idea: Lexicality is less important than grammatical features like verb form, presence of a verb auxiliary, . . .

- Rules are not systematically specified down to the level of lexical items.
- No semantic lexicalization for nouns, such as "$\text{NP}_{\text{stocks}}$".
- Instead: Structural "lexicalization", such as "$\text{NP}^{\text{S}}_{\text{CC}}$".

  Meaning: Parent node is "S" and noun phrase is coordinating.
- Keep functional lexicalization of closed-class words, such as "VB-have".
- Extension: learn the information that is stored for each non-terminal from the annotations. [Petrov and Knight, 2007]

Phrase Structure Grammars

Linearized parsing [Vinyals, Kaiser, et al., 2015]

Idea: Linearize the parse tree into a sequence and use sequence2seqence methods.

Linearize with a depth-first traversal of the parse tree. Output:

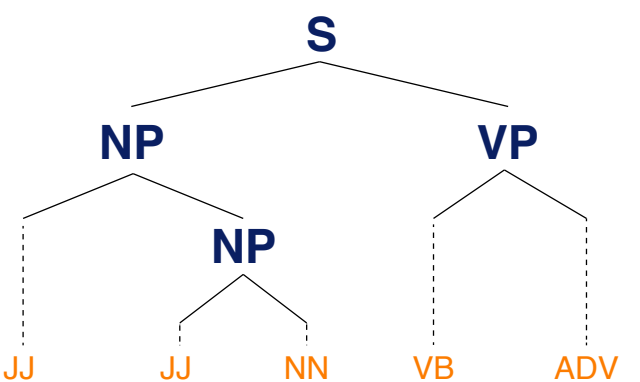
(S `At the start of the traversal`
(D `If descending to a non-terminal` **D**
$)_A$ `If ascending from a non-terminal` **A**
t `If descending to a terminal` **t**
$)_S$ `At the end of the traversal`

Example with total outputs after each state:

1. `(S`
2. `(S (NP`
3. `(S (NP JJ`
4. `(S (NP JJ (NP`
5. `(S (NP JJ (NP JJ`
6. `(S (NP JJ (NP JJ NN`
7. `(S (NP JJ (NP JJ NN )`$_{NP}$

`...`

14. `(S (NP JJ (NP JJ NN )`$_{NP}$ `)`$_{NP}$ `(VP VB ADV)`$_{VP}$ `)`$_S$



Remarks:

- Vinyals, Kaiser, et al. present linearaization as “Grammar as a Foreign Language”.
- They use a standard (in 2015 SoTA) machine translation neural network: an Encoder produces a representation of the text and a Decoder predicts the linearized parse tree.

Phrase Structure Grammars

Evaluation [Sekine and Collins, evalb]

Idea: Each constituent spans a range of text and has a label.

- Define each constituent as a triple `(label, start, end)`.
- A good hypothesis parse finds many triples that are in (recall) and few that are not in (precision) the reference parse.

Parsers are evaluated with the harmonic mean (F_1) of the averaged precision (LP) and labeled recall (LR):

$$\text{LP} = \frac{|\text{Correctly found triples in hypothesis parse}|}{|\text{Triples in hypothesis parse}|}$$

$$\text{LR} = \frac{|\text{Correctly found triples in hypothesis parse}|}{|\text{Triples in reference parse}|}$$

$$F_1 = \frac{2 \cdot LP \cdot LR}{LP + LR}$$

Phrase Structure Grammars

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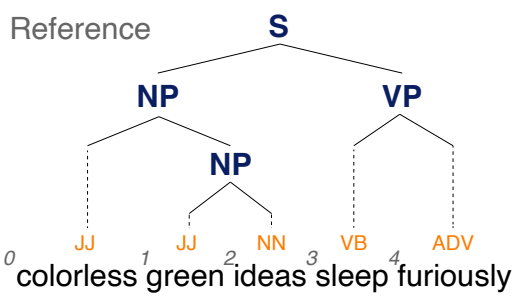
$$\text{LR} = \frac{|\text{Correctly found triples in hypothesis parse}|}{|\text{Triples in reference parse}|}$$

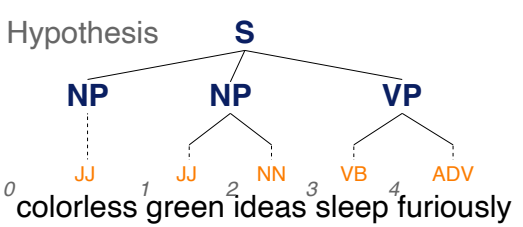
$$F_1 = \frac{2 \cdot LP \cdot LR}{LP + LR}$$

	Constituent Triples			
Reference parse	S(0,4)	NP(0,2)	NP(1,2)	VP(3,4)
Hypothesis parse	S(0,4)	NP(0,0)	NP(1,2)	VP(3,4)

$$LP = \frac{3}{4} \qquad LR = \frac{3}{4}$$

$$F_1 = \frac{2 \cdot 0.75 \cdot 0.75}{0.75 + 0.75} = 0.75$$





Remarks:

- Those evaluation measures were developed at the `PARSEVAL` Workshop in 1998 and are often refered with this name.
- Evalb is the reference implementation of the `PARSEVAL` measures.
- Evalb also includes the `cross-bracket` and `unlabeled P/R` metrtics.

Phrase Structure Grammars

Evaluation: Comparison of Methods

- All in exactly the same setting on the Penn Treebank.

Approach	Source	Labeled F_1
Extended CKY parsing	[Charniak, 1997]	0.73
Lexicalized parsing	[Collins, 1999]	0.89
Unlexicalized parsing	[Klein and Manning, 2003]	0.86
Learned unlexicalized parsing	[Petrov and Klein, 2007]	0.90
Combining parsers (Ensemble)	[Fossum and Knight, 2009]	0.92
Linearized parsing (Learning)	[Vinyals, Kaiser, et al., 2015]	0.92
CKY + learned disambiguation	[Zhang et al., 2020]	**0.96**

- Besides F_1 score, the time to parse 1,000 sentences is often considered too.
- Linearized methods are usually very fast. Ensemble methodes perform well but are slow.
- CKY profits a lot from batching and parallelization.