CKY Parsing

Ling571
Deep Processing Approaches to NLP
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Roadmap

- CKY parsing algorithm
  - Dynamic programming structure
  - Algorithm and example
  - Analysis & Discussion
- Probabilistic CFGs
  - Motivation: Ambiguity
  - Augmenting CFGs with probabilities

CKY

- Given an input string S of length n,
  - Build table (n+1) x (n+1)
  - Indexes correspond to inter-word positions
    - E.g., 0 Book 1 That 2 Flight 3
- Cells [i,j] contain SETS of non-terminals of ALL constituents spanning i,j
  - [j-1,j] contains pre-terminals
  - If [0,n] contains Start, the input is recognized

CKY Algorithm

function CKY-PARSE(*words*, *grammar*) **returns** *table*

for $j \leftarrow$ **from** 1 **to** LENGTH(*words*) **do**

$table[j-1, j] \leftarrow \{A \mid A \rightarrow words[j] \in grammar\}$

for $i \leftarrow$ **from** $j-2$ **downto** 0 **do**

for $k \leftarrow i+1$ **to** $j-1$ **do**

$table[i,j] \leftarrow table[i,j] \cup$

$\{A \mid A \rightarrow BC \in grammar,$

$B \in table[i,k],$

$C \in table[k,j]\}$

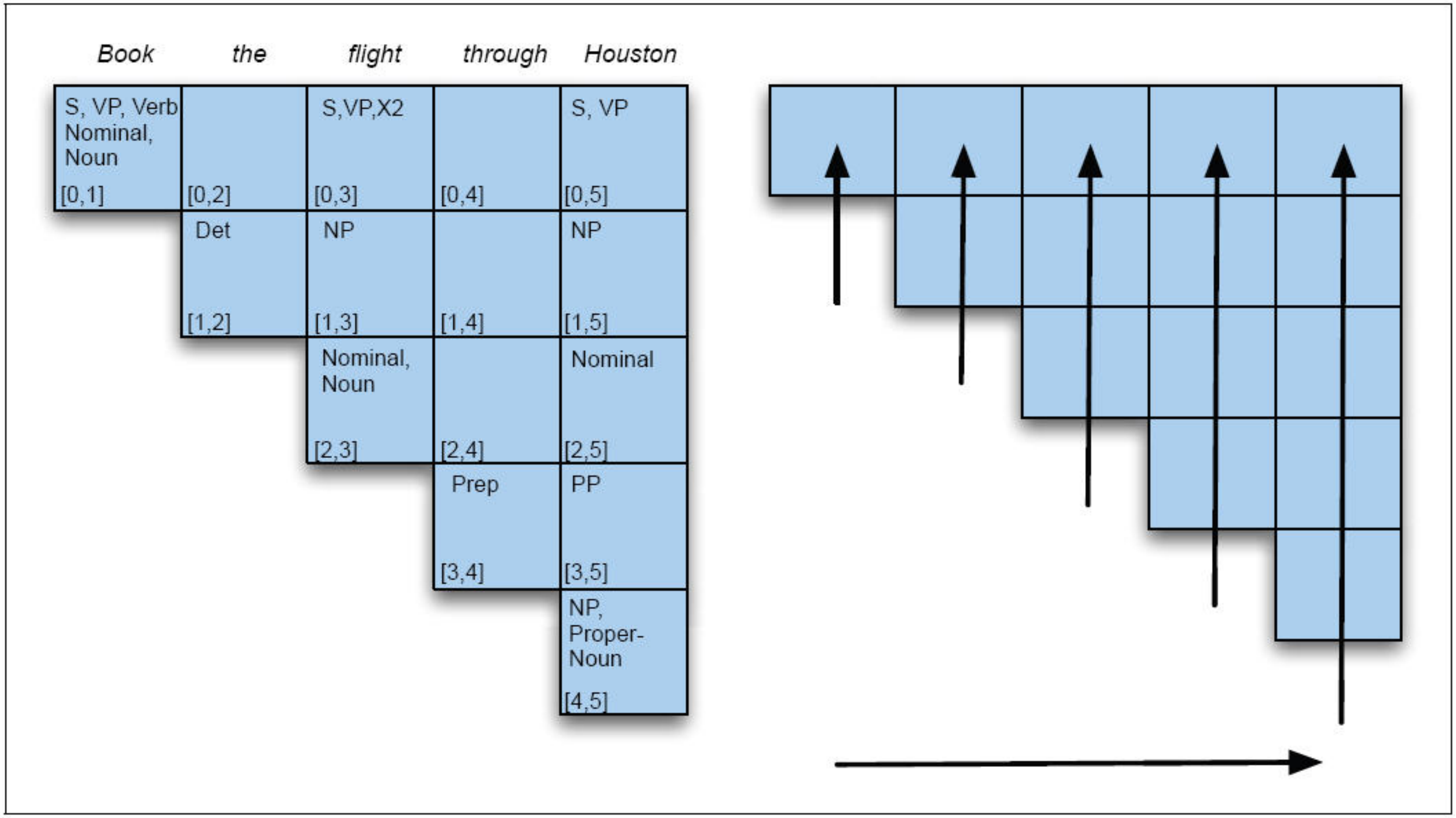
Is this a parser?

CKY Algorithm

- Table fills:
  - Column-by-column
  - Left-to-right
  - Bottom-to-top

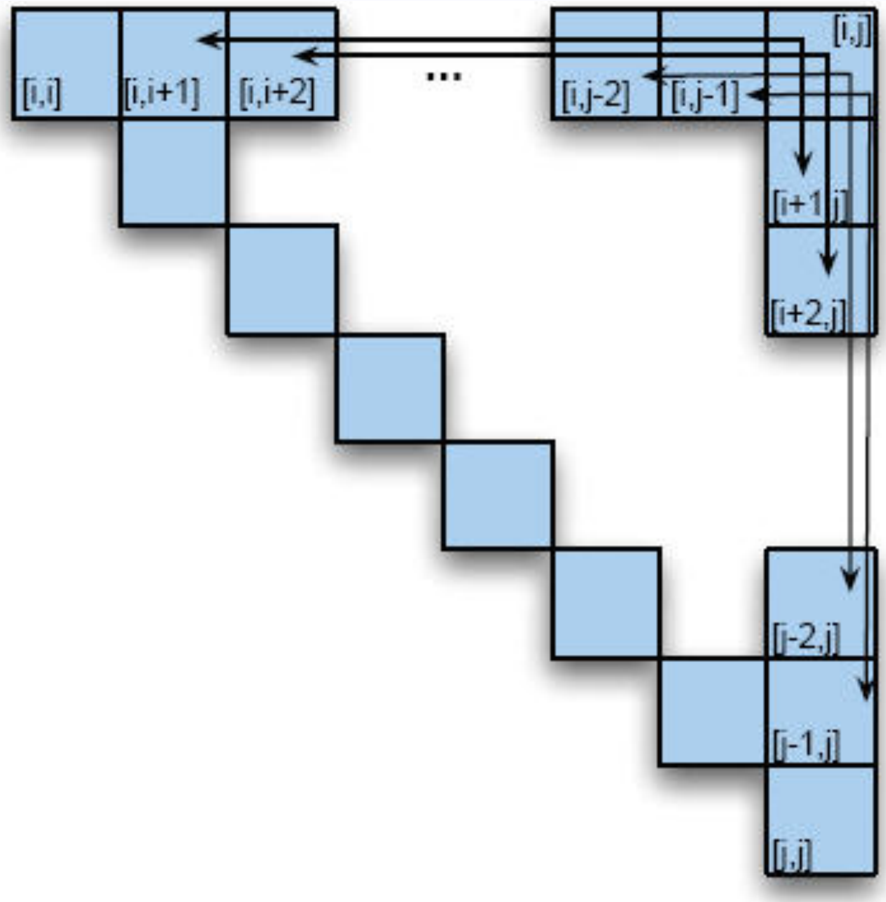
- Why?
  - Necessary info available (below and left)
  - Allows online sentence analysis
    - Works across input string as it arrives

CKY Table



Book
the
flight
through
Houston
S, VP, Verb Nominal, Noun
[0,1]
[0,2]
S,VP,X2
[0,3]
[0,4]
S, VP
[0,5]
Det
[1,2]
NP
[1,3]
[1,4]
NP
[1,5]
Nominal, Noun
[2,3]
[2,4]
Nominal
[2,5]
Prep
[3,4]
PP
[3,5]
NP, Proper-Noun
[4,5]

Filling CKY cell



0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]					

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]					
	Verb,VP,S [1,2]				

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]				
	Verb,VP,S [1,2]				

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]				
	Verb,VP,S [1,2]				
		Det [2,3]			

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I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]				
	Verb,VP,S [1,2]	[1,3]			
		Det [2,3]			

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]			
	Verb,VP,S [1,2]	[1,3]			
		Det [2,3]			
			NN, Nom [3,4]		

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I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]			
	Verb,VP,S [1,2]	[1,3]			
		Det [2,3]	NP [2,4]		
			NN, Nom [3,4]		

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]			
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]		
		Det [2,3]	NP [2,4]		
			NN, Nom [3,4]		

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I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]		
		Det [2,3]	NP [2,4]		
			NN, Nom [3,4]		

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0.5]	
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]	[1,5]	
		Det [2,3]	NP [2,4]	[2,5]	
			NN, Nom [3,4]	[3,5]	
				Prep [4,5]	

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0.5]	
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]	[1,5]	
		Det [2,3]	NP [2,4]	[2,5]	
			NN, Nom [3,4]	[3,5]	
				Prep [4,5]	
					NNP, NP [5,6]

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0.5]	
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]	[1,5]	
		Det [2,3]	NP [2,4]	[2,5]	
			NN, Nom [3,4]	[3,5]	
				Prep [4,5]	PP [4,6]
					NNP, NP [5,6]

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	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]	[1,5]	
		Det [2,3]	NP [2,4]	[2,5]	NP [2,6]
			NN, Nom [3,4]	[3,5]	Nom [3,6]
				Prep [4,5]	PP [4,6]
					NNP, NP [5,6]

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I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0.5]	
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]	[1,5]	VP,XP2,S [1,6]
		Det [2,3]	NP [2,4]	[2,5]	NP [2,6]
			NN, Nom [3,4]	[3,5]	Nom [3,6]
				Prep [4,5]	PP [4,6]
					NNP, NP [5,6]

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0.5]	S [0,6]
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]	[1,5]	VP,XP2,S [1,6]
		Det [2,3]	NP [2,4]	[2,5]	NP [2,6]
			NN, Nom [3,4]	[3,5]	Nom [3,6]
				Prep [4,5]	PP [4,6]
					NNP, NP [5,6]

From Recognition to Parsing

- Limitations of current recognition algorithm:
  - Only stores non-terminals in cell
    - Not rules or cells corresponding to RHS
  - Stores SETS of non-terminals
    - Can't store multiple rules with same LHS

- Parsing solution:
  - All repeated versions of non-terminals
  - Pair each non-terminal with pointers to cells
    - Backpointers
  - Last step: construct trees from back-pointers in [0,n]

0 I 1 prefer 2 a 3 flight 4 on 5 TWA 6

I	prefer	a	flight	on	TWA
NP,Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0.5]	S_1, S_2, S_3 [0,6]
	Verb,VP,S [1,2]	[1,3]	VP,XP2,S [1,4]	[1,5]	VP_1,VP_2,VP_3, ,XP2,S_1,S_2,S_3 [1,6]
		Det [2,3]	NP [2,4]	[2,5]	NP [2,6]
			NN, Nom [3,4]	[3,5]	Nom [3,6]
				Prep [4,5]	PP [4,6]
					NNP, NP [5,6]

CKY Discussion

- Running time:
  - $O(n^3)$ where *n* is the length of the input string
  - Inner loop grows as square of # of non-terminals

- Expressiveness:
  - As implemented, requires CNF
    - Weakly equivalent to original grammar
    - Doesn't capture full original structure
      - Back-conversion?
        - Can do binarization, terminal conversion
        - Unit non-terminals require change in CKY

Parsing: PCFGs

Ling 571
Deep Processing Techniques for NLP
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Roadmap

- Probabilistic Context-free Grammars (PCFGs)
  - Motivation: Ambiguity
  - Approach:
    - Definition
    - Disambiguation
    - Parsing
    - Evaluation
    - Enhancements

- What about ambiguity?
- CKY can represent it
- Can’t resolve it

Probabilistic Parsing

- Provides strategy for solving disambiguation problem
  - Compute the probability of all analyses
  - Select the most probable
- Employed in language modeling for speech recognition
  - N-gram grammars predict words, constrain search
  - Also, constrain generation, translation

PCFGs

- Probabilistic Context-free Grammars
  - Augmentation of CFGs

N	a set of **non-terminal symbols** (or **variables**)
Σ	a set of **terminal symbols** (disjoint from N)
R	a set of **rules** or productions, each of the form $A \rightarrow \beta$ $[p]$, where A is a non-terminal, β is a string of symbols from the infinite set of strings $(\Sigma \cup N)*$, and p is a number between 0 and 1 expressing $P(\beta\|A)$
S	a designated **start symbol**

PCFGs

- Augment each production with probability that LHS will be expanded as RHS
  - P(A→B) or P(A→B|A), P(RHS|LHS)
  - Sum over all possible expansions is 1

$$\sum_{\beta} P(A \rightarrow \beta) = 1$$

- A PCFG is consistent if sum of probabilities of all sentences in language is 1.
  - Recursive rules often yield inconsistent grammars

Example PCFG

Grammar		
S → *NP VP*	[.80]
S → *Aux NP VP*	[.15]
S → *VP*	[.05]
NP → *Pronoun*	[.35]
NP → *Proper-Noun*	[.30]
NP → *Det Nominal*	[.20]
NP → *Nominal*	[.15]
Nominal → *Noun*	[.75]
Nominal → *Nominal Noun*	[.20]
Nominal → *Nominal PP*	[.05]
VP → *Verb*	[.35]
VP → *Verb NP*	[.20]
VP → *Verb NP PP*	[.10]
VP → *Verb PP*	[.15]
VP → *Verb NP NP*	[.05]
VP → *VP PP*	[.15]
PP → *Preposition NP*	[1.0]

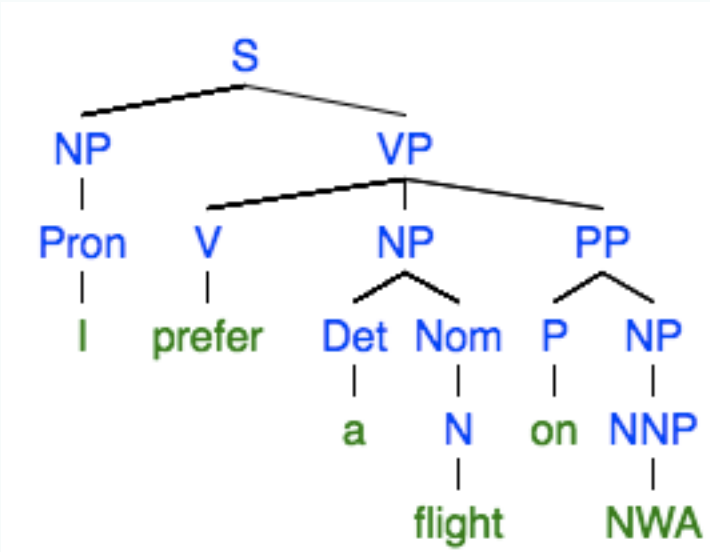
Lexicon
Det → *that* [.10] | *a* [.30] | *the* [.60]
Noun → *book* [.10] | *flight* [.30]
| *meal* [.15] | *money* [.05]
| *flights* [.40] | *dinner* [.10]
Verb → *book* [.30] | *include* [.30]
| *prefer*; [.40]
Pronoun → *I* [.40] | *she* [.05]
| *me* [.15] | *you* [.40]
Proper-Noun → *Houston* [.60]
| *NWA* [.40]
Aux → *does* [.60] | *can* [40]
Preposition → *from* [.30] | *to* [.30]
| *on* [.20] | *near* [.15]
| *through* [.05]

Disambiguation

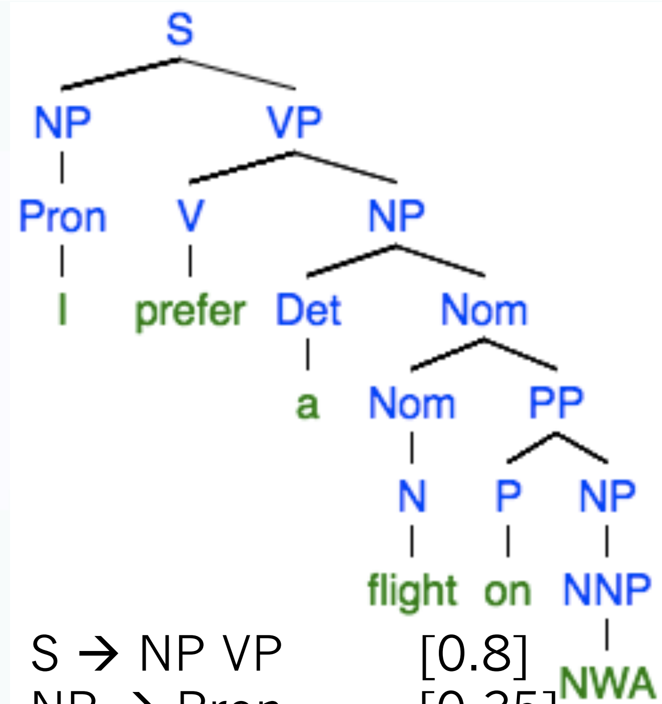
- A PCFG assigns probability to each parse tree T for input S.
  - Probability of T: product of all rules to derive T

$$P(T,S) = \prod_{i=1}^{n} P(RHS_i \mid LHS_i)$$

$$P(T,S) = P(T)P(S \mid T) = P(T)$$



S → NP VP [0.8]
NP → Pron [0.35]
Pron → I [0.4]
VP → V NP PP [0.1]
V → prefer [0.4]
NP → Det Nom [0.2]
Det → a [0.3]
Nom → N [0.75]
N → flight [0.3]
PP → P NP [1.0]
P → on [0.2]
NP → NNP [0.3]
NNP → NWA [0.4]



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NP → Pron [0.35]
Pron → I [0.4]
VP → V NP [0.2]
V → prefer [0.4]
NP → Det Nom [0.2]
Det → a [0.3]
Nom → Nom PP [0.05]
Nom → N [0.75]
N → flight [0.3]
PP → P NP [1.0]
P → on [0.2]
NP → NNP [0.3]
NNP → NWA [0.4]

Parsing Problem for PCFGs

- Select T such that:

$$\hat{T}(S) = \underset{T s.t, S = yield(T)}{\operatorname{argmax}} P(T)$$

  - String of words S is *yield* of parse tree over S
  - Select tree that maximizes probability of parse