Announcement

- Programming Assignment 6
  - Due: Dec. 16, 11:59pm

Project

- Proposal presentation
  - Dec. 14, 16
    - Schedule will be announced next week
  - 5min per group
  - To introduce your topic, motivation, possible methods
  - Talk to me or TAs if you have any question or concern

Project

- Usage of external code and tools not prohibited.
- But…
  - The core component and algorithms of your project should be implemented by yourself.
  - In your final presentation and report, list all the external resources that you use and explain how/why you use them.
  - After the final presentation, you will be asked to submit your source code along with your final project report.

Next Week

- Dec. 7, Wed
  - Computer vision by Prof. Sibei Yang
- Dec. 9, Fri
  - No class

Natural Language Processing

AIMA Ch 23

[Some slides were adapted from slides by James H. Martin at U Colorado Boulder, by Albert Gatt at University of Malta, and by Eric Xing of CMU]

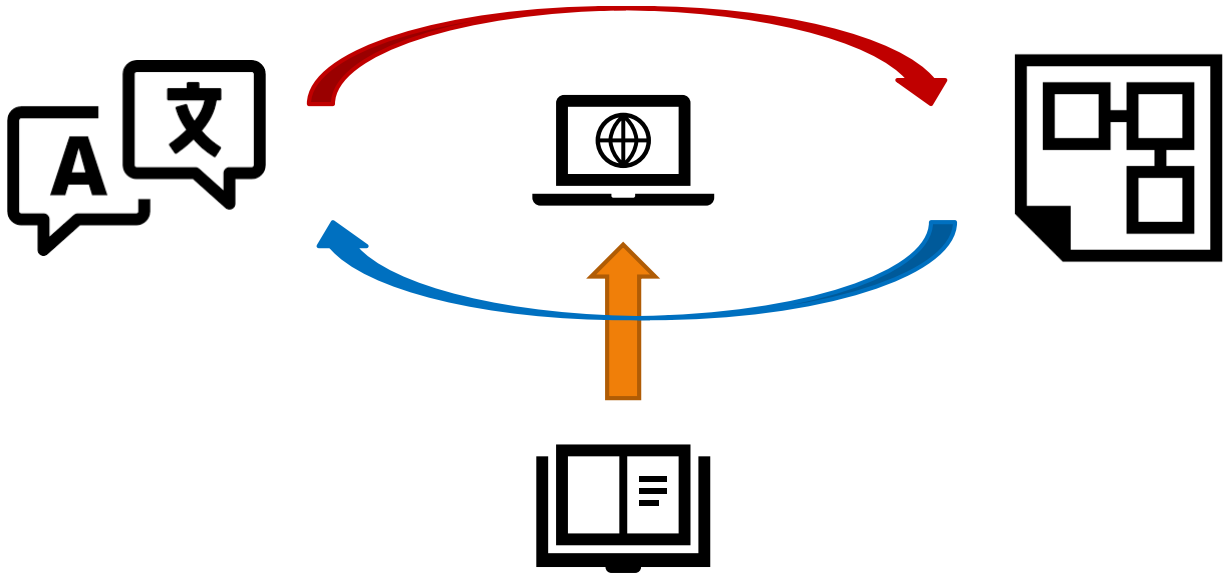
Additional Reference

- [SLP] Speech and Language Processing, Daniel Jurafsky and James H. Martin
  - 2nd edition, 2008
  - 3rd edition, Dec. 2021

- Parsing
  - [AIMA] Ch 23
  - [SLP] Ch 12, 13, 14

What is NLP?

- Automating the analysis, generation, and acquisition of human (“natural”) language



NLP Applications

- ChatBot
  - Question answering, conversation
- Machine translation
- Information extraction
  - From financial and law documents, e-commerce websites, etc.
- Chinese IME
- Grammatical checker
- Essay scoring
- News generation

Levels of NLP Research

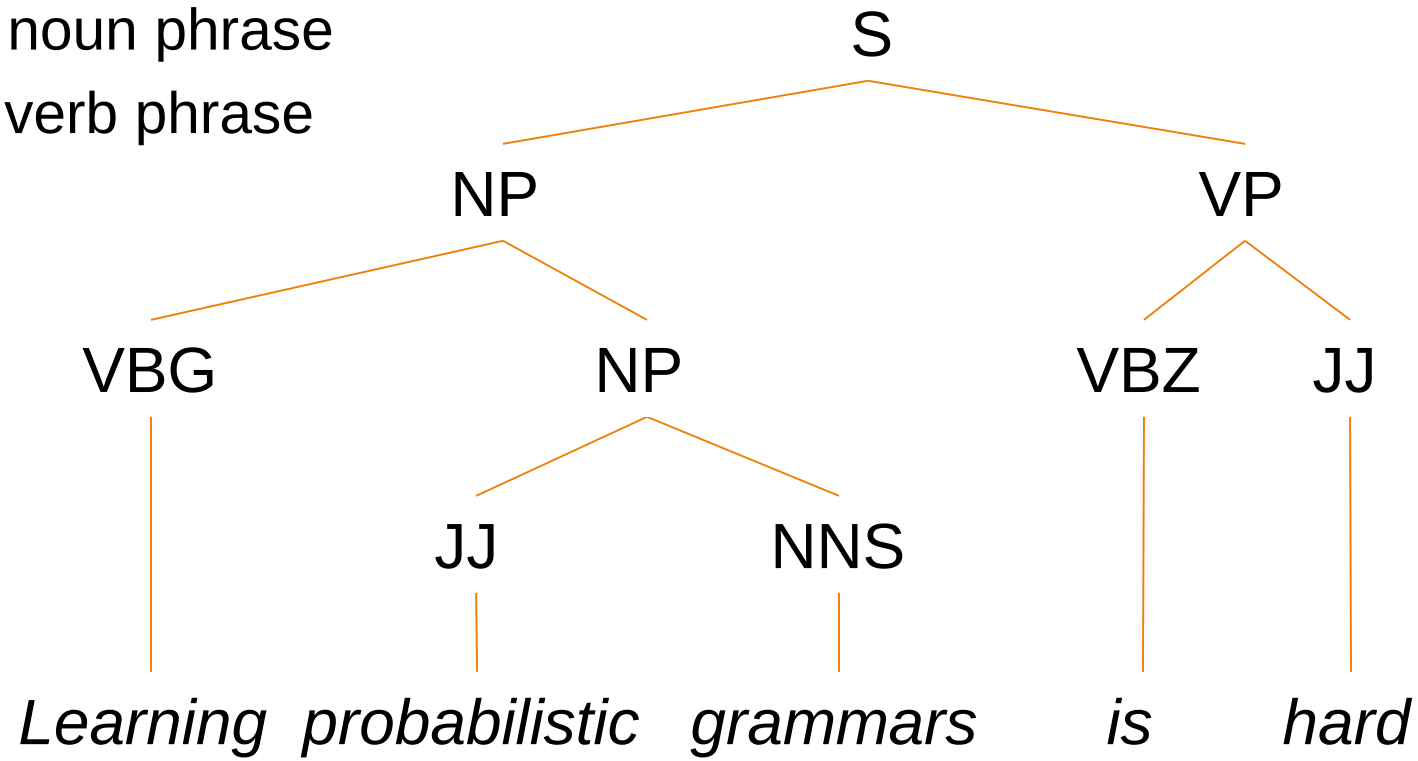
Take CS274A!

Phonetics and phonology	knowledge about linguistic sounds
Morphology	knowledge of the meaningful components of words
Syntax	knowledge of the structural relationships between words
Lexical semantics	knowledge of word meaning
Compositional semantics	knowledge of the meaning of sentences
Pragmatics	knowledge of the relationship of meaning to the goals and intentions of the speaker
Discourse	knowledge about linguistic units larger than a single sentence

Constituency Parsing

Constituent parse tree

- Also called a phrase structure parse
- Each non-leaf node represents a phrase (i.e., constituent)
  - S: sentence
  - NP: noun phrase
  - VP: verb phrase
  - …



Grammars

- Grammar
  - the set of constituents and the rules that govern how they combine
- Lots of different theories of grammar
- Context-free grammars (CFGs)
  - Also known as: Phrase structure grammars
  - One of the simplest and most basic grammar formalisms

Context-Free Grammars

- A context-free grammar has four components
  - A set Σ of terminals (words)
  - A set N of nonterminals (phrases)
  - A start symbol $S \in N$
  - A set R of production rules
    - Specifies how a nonterminal can produce a string of terminals and/or nonterminals

Example Grammar

Grammar Rules			Examples
S	→	*NP VP*	I + want a morning flight
NP	→	*Pronoun*	I
	|	*Proper-Noun*	Los Angeles
	|	*Det Nominal*	a + flight
Nominal	→	*Nominal Noun*	morning + flight
	|	*Noun*	flights
VP	→	*Verb*	do
	|	*Verb NP*	want + a flight
	|	*Verb NP PP*	leave + Boston + in the morning
	|	*Verb PP*	leaving + on Thursday
PP	→	*Preposition NP*	from + Los Angeles

Example Grammar

Noun →	*flights* | *breeze* | *trip* | *morning*
Verb →	*is* | *prefer* | *like* | *need* | *want* | *fly*
Adjective →	*cheapest* | *non-stop* | *first* | *latest* | *other* | *direct*
Pronoun →	*me* | *I* | *you* | *it*
Proper-Noun →	*Alaska* | *Baltimore* | *Los Angeles* | *Chicago* | *United* | *American*
Determiner →	*the* | *a* | *an* | *this* | *these* | *that*
Preposition →	*from* | *to* | *on* | *near*
Conjunction →	*and* | *or* | *but*

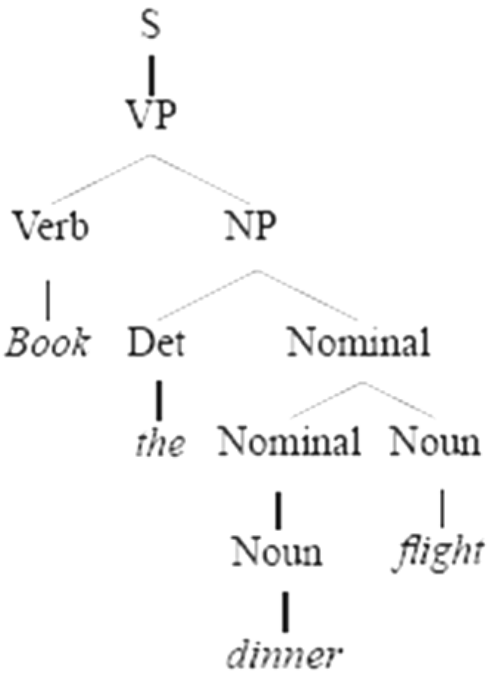
Sentence Generation

- A grammar can be used to generate a string
  - starting from a string containing only the start symbol S
  - recursively applying the rules to rewrite the string
  - until the string contains only terminals
- The generative process specifies the grammatical structure (parse tree) of the string

Example

$S \rightarrow NP\ VP$
$S \rightarrow Aux\ NP\ VP$
$S \rightarrow VP$
$NP \rightarrow Pronoun$
$NP \rightarrow Proper\text{-}Noun$
$NP \rightarrow Det\ Nominal$
$NP \rightarrow Nominal$
$Nominal \rightarrow Noun$
$Nominal \rightarrow Nominal\ Noun$
$Nominal \rightarrow Nominal\ PP$
$VP \rightarrow Verb$
$VP \rightarrow Verb\ NP$
$VP \rightarrow Verb\ NP\ PP$
$VP \rightarrow Verb\ PP$
$VP \rightarrow Verb\ NP\ NP$
$VP \rightarrow VP\ PP$
$PP \rightarrow Preposition\ NP$

.....



Book the dinner flight

Sentence Parsing

- Parsing is the process of taking a string and a grammar and returning one or more parse tree(s) for that string
  - If no parse tree can be found, then the string does not belong to the language
  - Parsing algorithms: CYK, Earley, etc.
    - To be introduced later

Probabilistic Grammars

- Also called stochastic grammars
- Each rule is associated with a probability

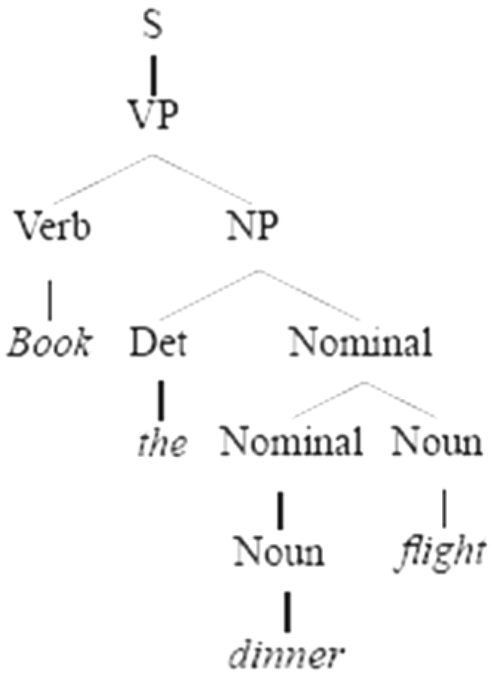
$$\alpha \rightarrow \beta : P(\alpha \rightarrow \beta | \alpha)$$

- The probability of a parse tree is the product of the probabilities of all the rules used in generating the parse tree

Example

$S \rightarrow NP\ VP$	[.80]
$S \rightarrow Aux\ NP\ VP$	[.15]
$S \rightarrow VP$	[.05]
$NP \rightarrow Pronoun$	[.35]
$NP \rightarrow Proper\text{-}Noun$	[.30]
$NP \rightarrow Det\ Nominal$	[.20]
$NP \rightarrow Nominal$	[.15]
$Nominal \rightarrow Noun$	[.75]
$Nominal \rightarrow Nominal\ Noun$	[.20]
$Nominal \rightarrow Nominal\ PP$	[.05]
$VP \rightarrow Verb$	[.35]
$VP \rightarrow Verb\ NP$	[.20]
$VP \rightarrow Verb\ NP\ PP$	[.10]
$VP \rightarrow Verb\ PP$	[.15]
$VP \rightarrow Verb\ NP\ NP$	[.05]
$VP \rightarrow VP\ PP$	[.15]
$PP \rightarrow Preposition\ NP$	[1.0]

.....



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$P(T) = .05 \times .20 \times .20 \times .20 \times .75 \times .30 \times .60 \times .10 \times .40 = 2.2 \times 10^{-6}$

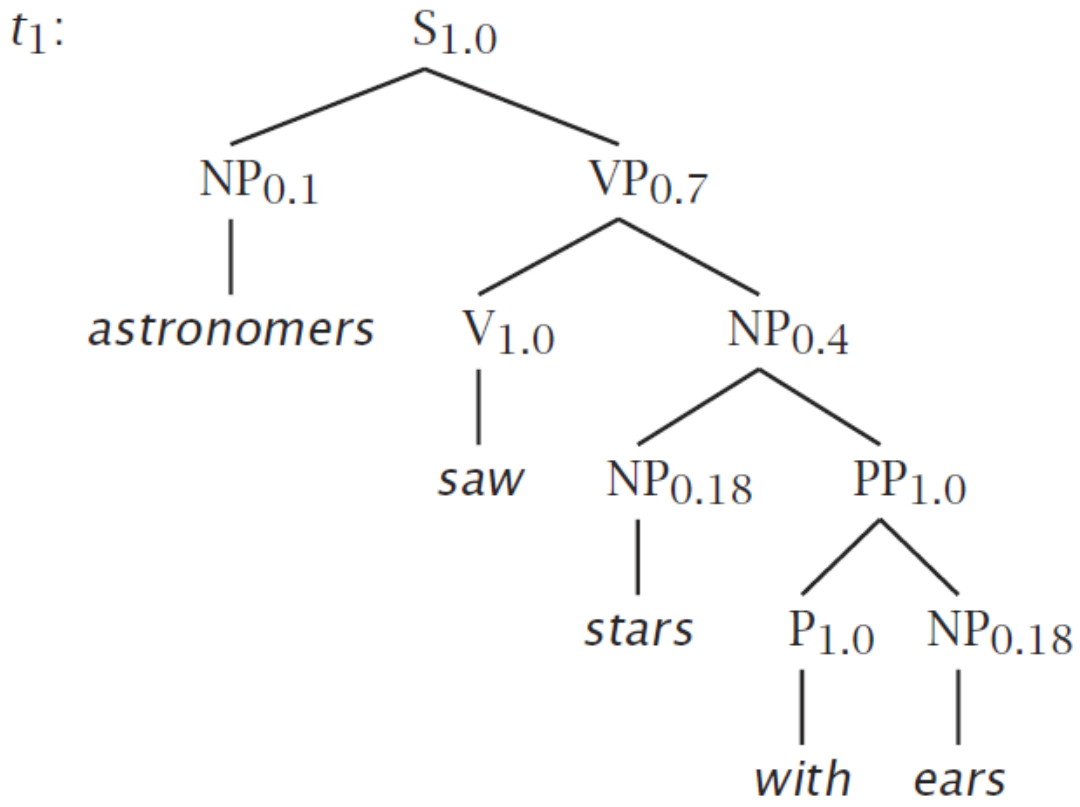
Ambiguity

- A sentence is ambiguous if it has more than one possible parse tree
  - …and hence more than one interpretation
- Examples
  - Astronomers saw stars with ears.

Example

S → NP VP	1.0	NP → NP PP	0.4
PP → P NP	1.0	NP → *astronomers*	0.1
VP → V NP	0.7	NP → *ears*	0.18
VP → VP PP	0.3	NP → *saw*	0.04
P → *with*	1.0	NP → *stars*	0.18
V → *saw*	1.0	NP → *telescopes*	0.1

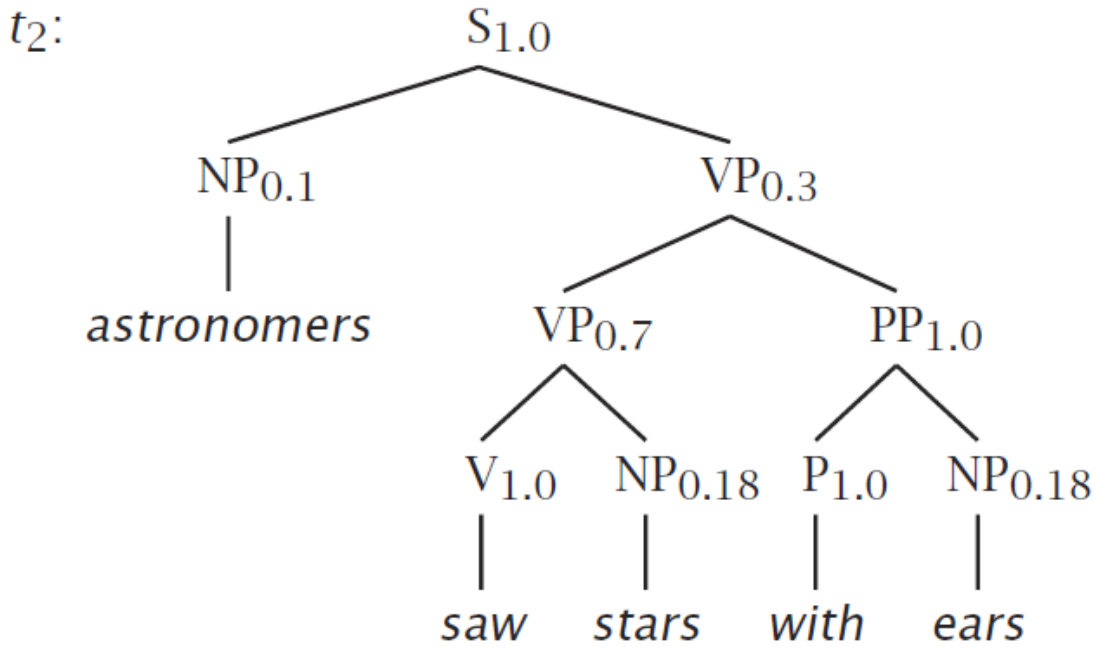
Example



$$P(t_1) = 1.0 \times 0.1 \times 0.7 \times 1.0 \times 0.4 \times 0.18 \times 1.0 \times 1.0 \times 0.18$$

$$= 0.0009072$$

Example



$$P(t_2) = 1.0 \times 0.1 \times 0.3 \times 0.7 \times 1.0 \times 0.18 \times 1.0 \times 1.0 \times 0.18$$

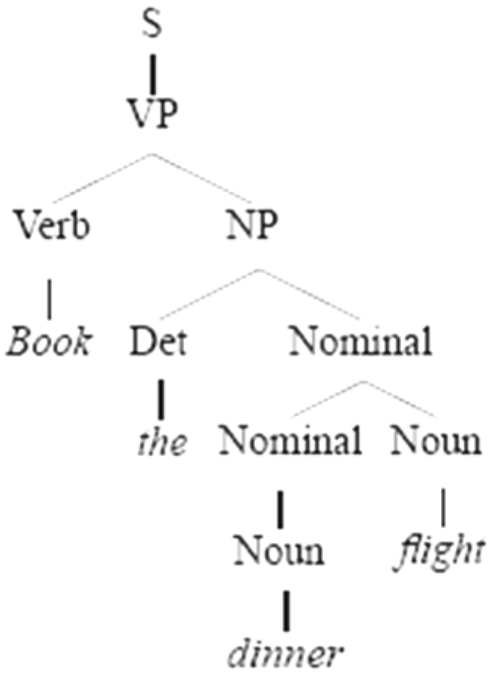
$$= 0.0006804$$

Parsing Algorithm

Parsing

- Parsing with CFGs is the task of assigning proper parse trees to input strings

Book the dinner flight



Parsing

- A brute-force approach
  - Enumerate all parse trees consistent with the input string
- Problem
  - Number of binary trees with *n* leaves is the Catalan number C_{n-1}
  - (Exponential growth)

Cocke–Younger–Kasami Algorithm (CYK)

- A bottom-up dynamic programming algorithm
- Applies to CFG in Chomsky Normal Form (CNF)
  - Only two types of production rules

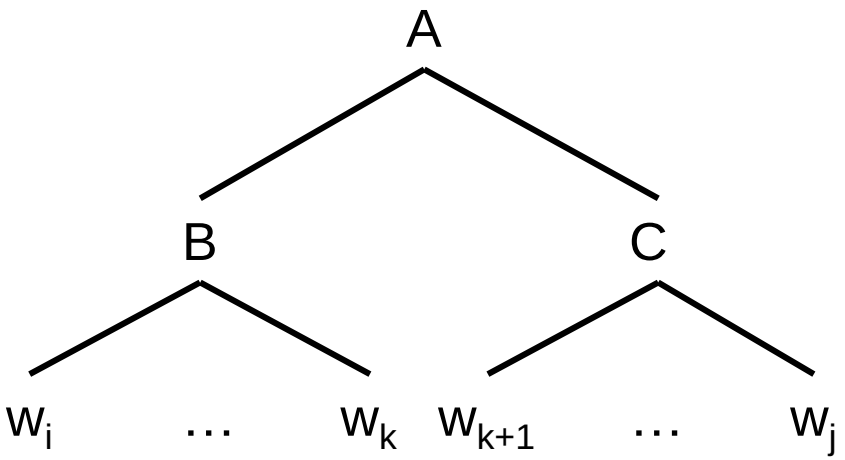
$A \rightarrow B\ C$

$A \rightarrow w$

- Any CFG can be converted into CNF
  - The resulting grammar accepts (and rejects) the same set of strings as the original grammar

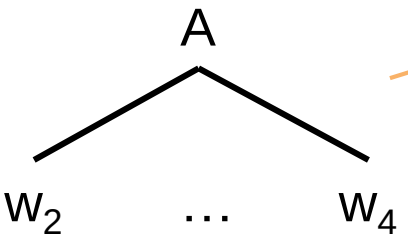
Parsing

- Dynamic programming
  - Divide the problem into many sub-problems
    - Sub-problem: parsing the substring between positions *i* and *j*
  - Solutions to smaller sub-problems are reused in solving larger sub-problems



CYK

- Build a table so that a non-terminal A spanning from i to j in the input is placed in cell [i-1, j] in the table.



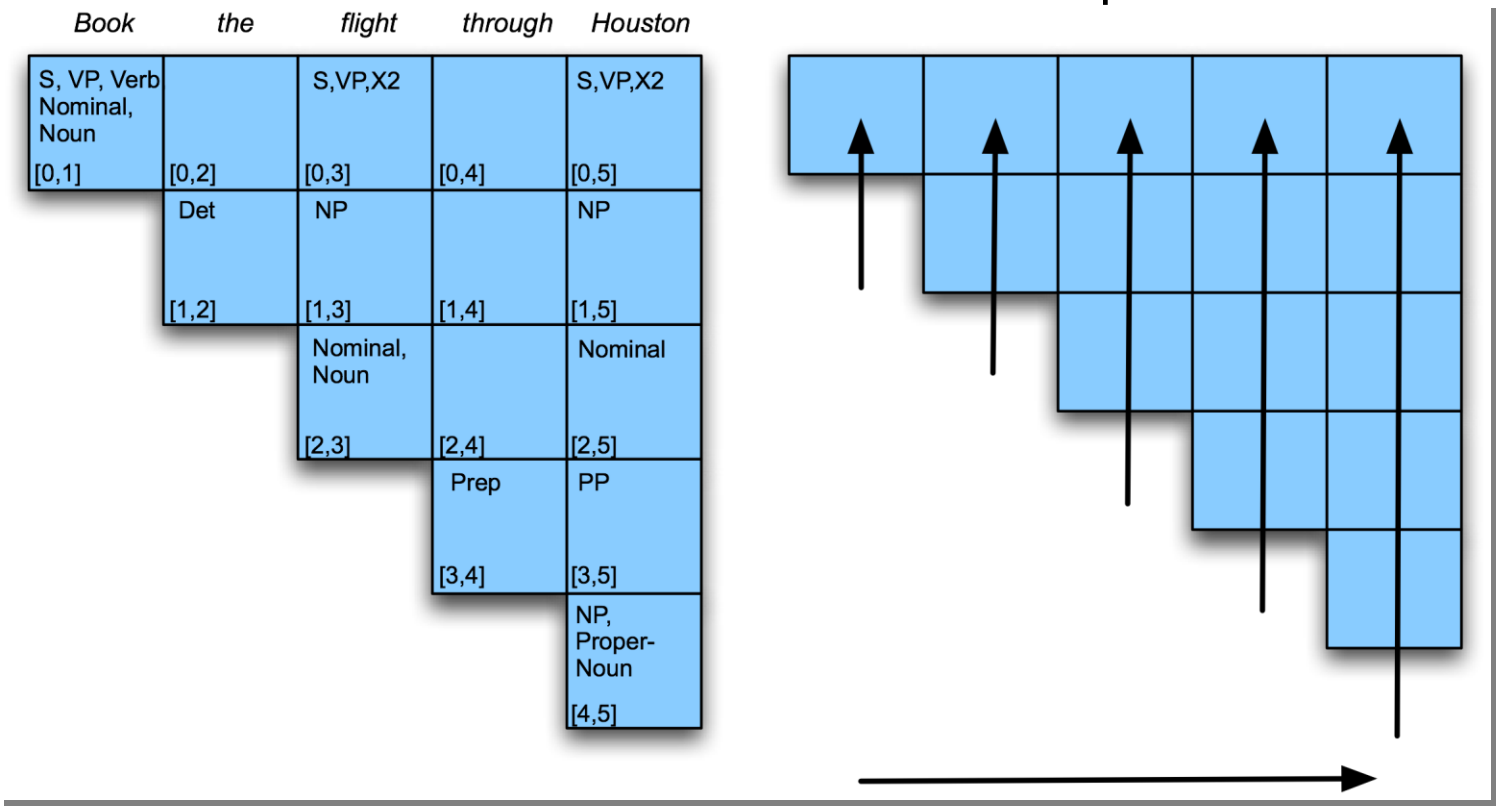
	1	2	3	4	5
0					
1				A	
2					
3					
4					

- So a non-terminal spanning an entire string will sit in cell [0, n]
  - Hopefully an *S*

Example

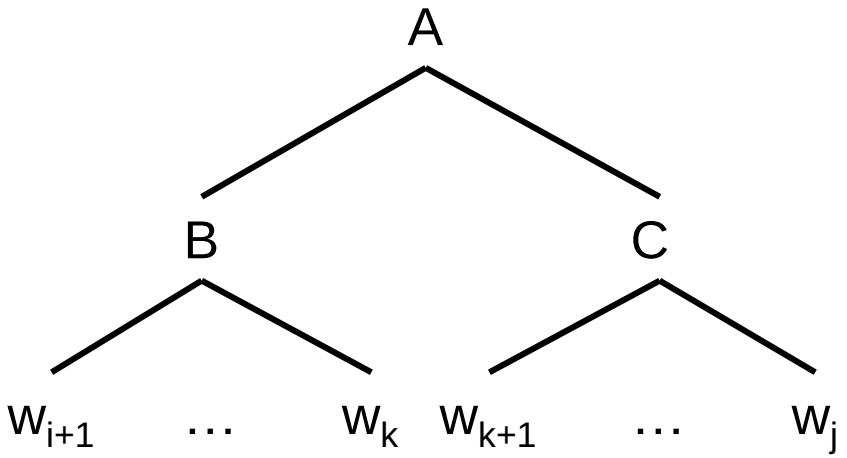
A completed table for input "Book the flight through Houston"

We fill the table from bottom up



CYK

- Base case:
  - A is in cell [i-1,i] iff. there exists a rule $A \rightarrow w_i$
- Recursion:
  - A is in cell [i,j] iff. for some rule $A \rightarrow B\ C$ there is a B in cell [i,k] and a C in cell [k,j] for some k.



CYK 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**
      $table[i,j] \leftarrow table[i,j] \cup$
        $\{A \mid A \rightarrow BC \in grammar,$
          $B \in table[i,k],$
          $C \in table[k,j]\}$

CYK

- *The flight includes a meal.*

Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0					
1					
2					
3					
4					

CYK

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- S → NP VP
- NP → Det N
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- V → includes
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- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det				
1					
2					
3					
4					

CYK

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Grammar

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- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det				
1		N			
2					
3					
4					

CYK

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Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det	NP			
1		N			
2					
3					
4					

CYK

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Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det	NP			
1		N			
2			V		
3					
4					

CYK

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Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det	NP			
1		N			
2			V		
3				Det	
4					

CYK

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- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det	NP			
1		N			
2			V		
3				Det	
4					N

CYK

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Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det	NP			
1		N			
2			V		
3				Det	NP
4					N

CYK

- *The flight includes a meal.*

Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det	NP			
1		N			
2			V		VP
3				Det	NP
4					N

CYK

- *The flight includes a meal.*

Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight

	1	2	3	4	5
0	Det	NP			S
1		N			
2			V		VP
3				Det	NP
4					N

CYK Parsing

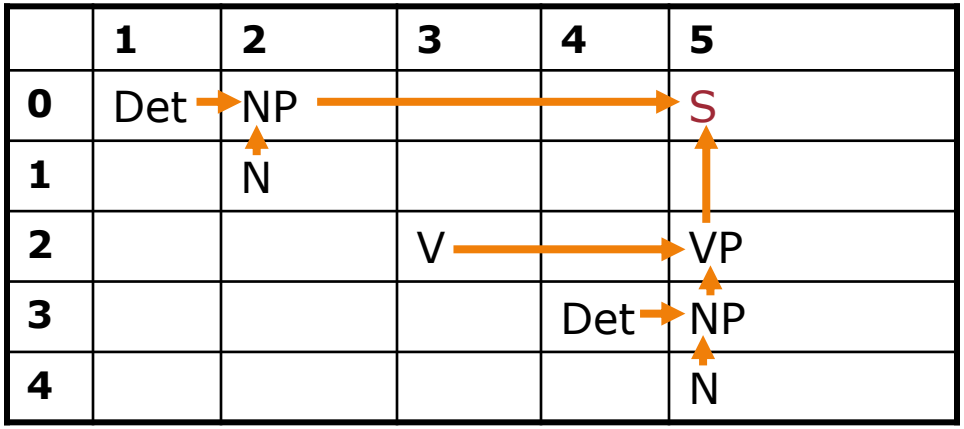
- Is that really a parser?
  - We want a parse tree, not a yes/no answer
- Simple changes
  - Add back-pointers so that each state knows where it came from.
  - After filling the table, recursively retrieve the constituents from the top (i.e., the start symbol) down

CYK

- *The flight includes a meal.*

Grammar

- S → NP VP
- NP → Det N
- VP → V NP
- V → includes
- Det → the
- Det → a
- N → meal
- N → flight



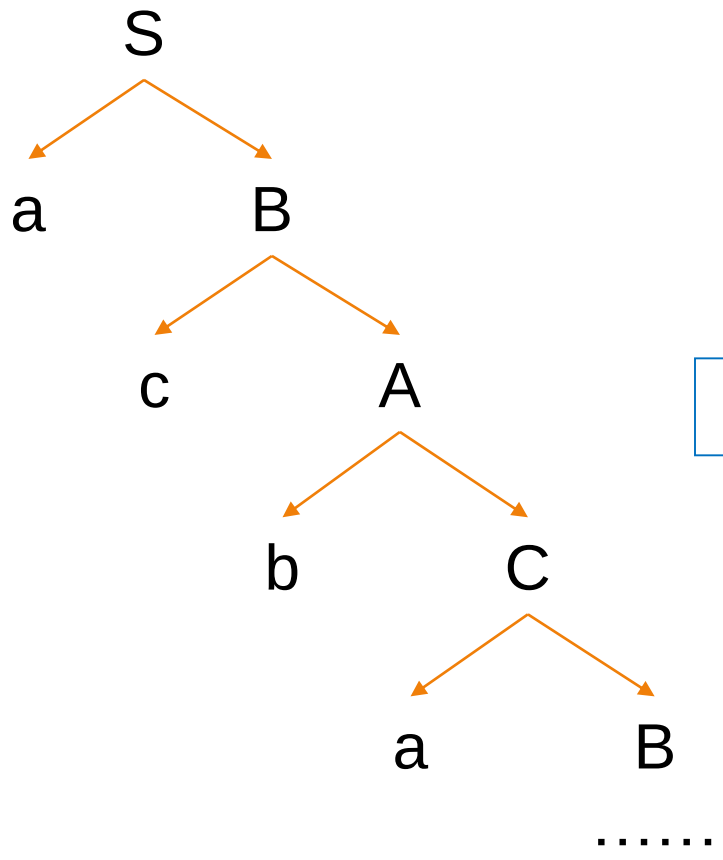
Probabilistic Parsing

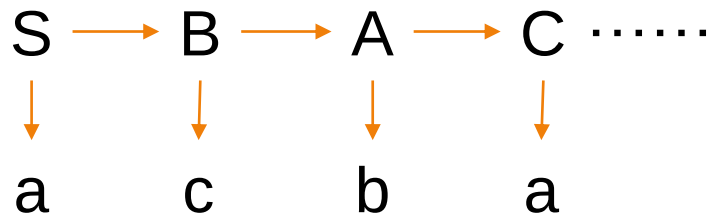
- What if we have a PCFG, and we want to find the parse tree of an input string with the highest probability?
- Still run CYK, but:
  - In cell [i-1,j] of the table, associate each nonterminal A with the probability of the best parse tree rooted at A covering substring from i to j
  - The probabilities can be computed with a bottom-up recursive formula during CYK steps

Regular Grammar

Regular Grammars

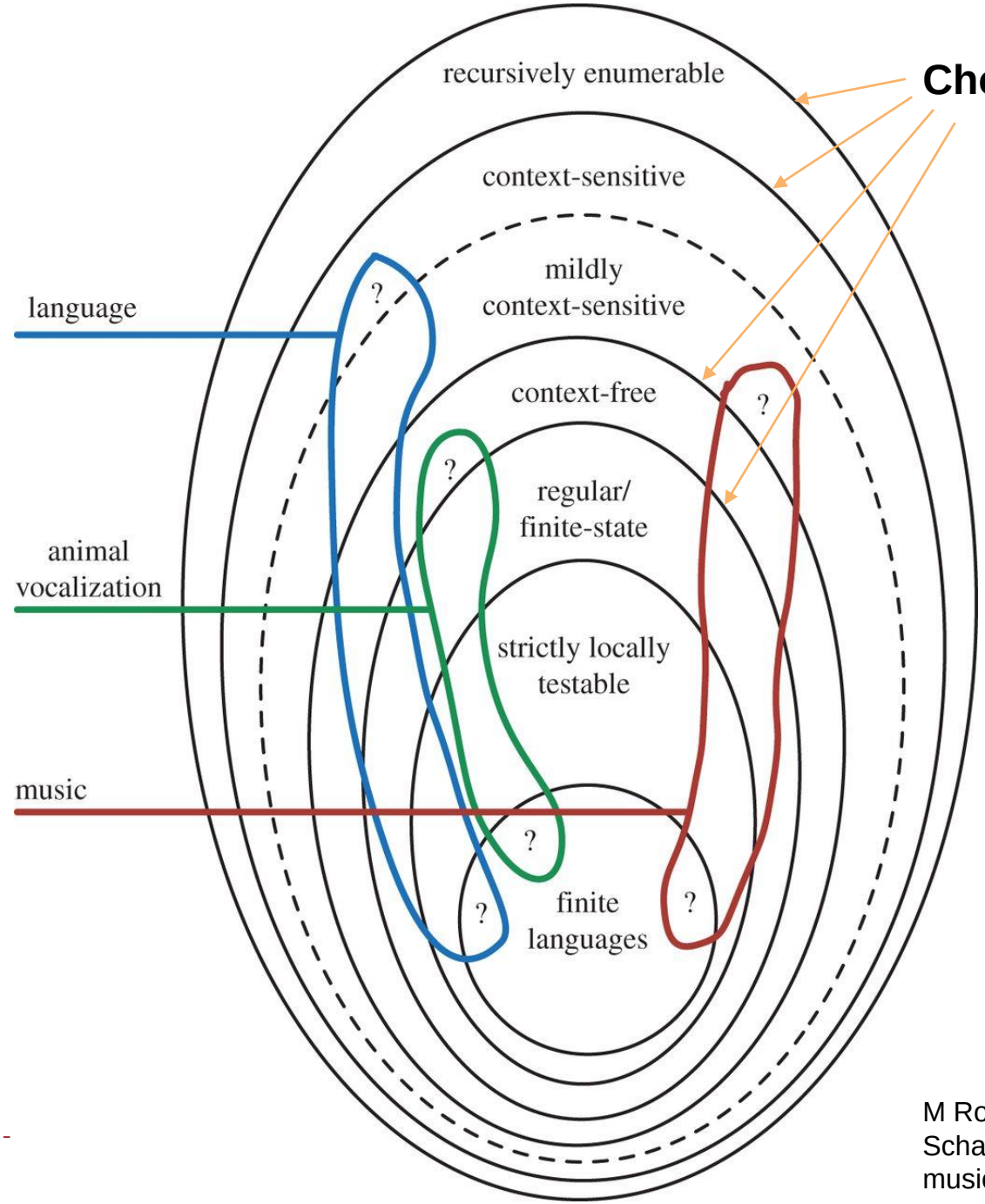
- Production rules are of the form $A \rightarrow aB$ *or* $A \rightarrow a$



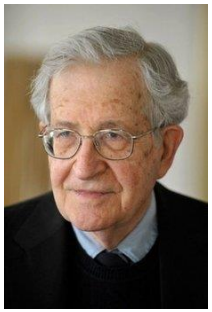


HMM = Probabilistic RG ⊂ PCFG

Viterbi ~ Probabilistic CYK



Chomsky Hierarchy

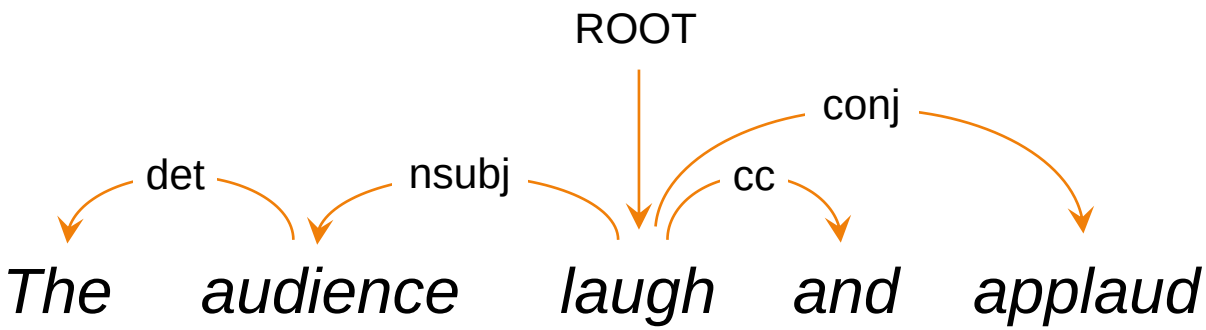


M Rohrmeier, W Zuidema, G Wiggins, C Scharff. Principles of structure building in music, language and animal song.

Dependency Parsing

Dependency Parse

- A dependency parse is a directed tree where
  - the nodes are the words in a sentence
    - ROOT: a special root node
  - The links between the words represent their dependency relations
    - Typically drawn as a directed arc from head to dependent
    - Dependency arcs may be typed (labeled)



Dependency Types

Argument Dependencies	Description
nsubj	nominal subject
csubj	clausal subject
dobj	direct object
iobj	indirect object
pobj	object of preposition
Modifier Dependencies	**Description**
tmod	temporal modifier
appos	appositional modifier
det	determiner
prep	prepositional modifier

Dependency Parsing

- Advantages
  - Deals well with free word order languages where the constituent structure is quite fluid
    - Ex: Czech, Turkish
  - Dependency parses of sentences having the same meaning are more similar across languages than constituency parses
  - Dependency structure often captures the syntactic relations needed by later applications
  - Parsing can be faster than CFG-bases parsers

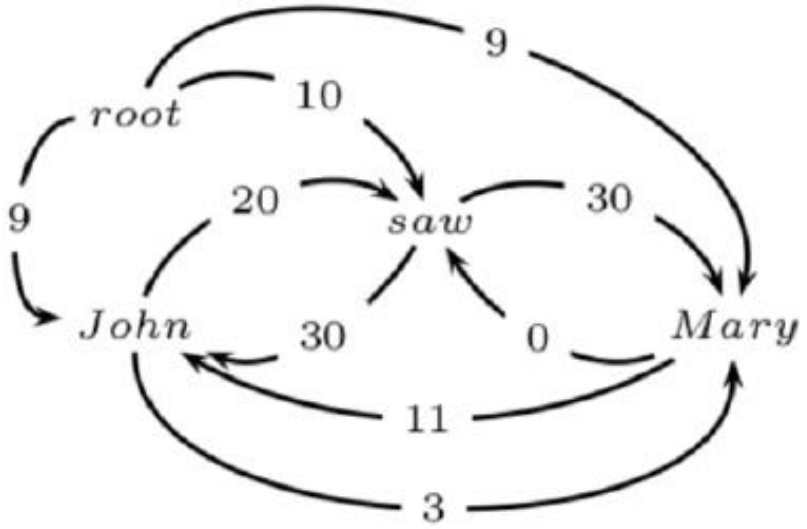
Dependency Parsing

- Parsing
  - Taking a string and a grammar and returning one or more parse tree(s) for that string
- Probabilistic parsing
  - Find the highest-scoring parse tree

- Several approaches to dependency parsing
  - Next: a brief intro of graph-based parsing

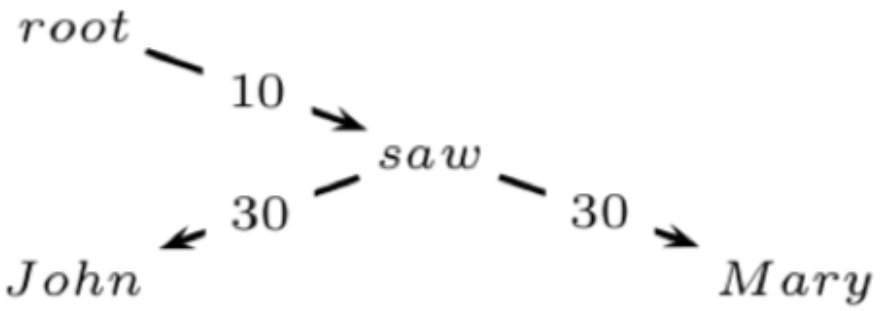
Graph-based parsing

- Each arc has a non-negative score.
  - An arc score is often computed from features of the two words and the context.



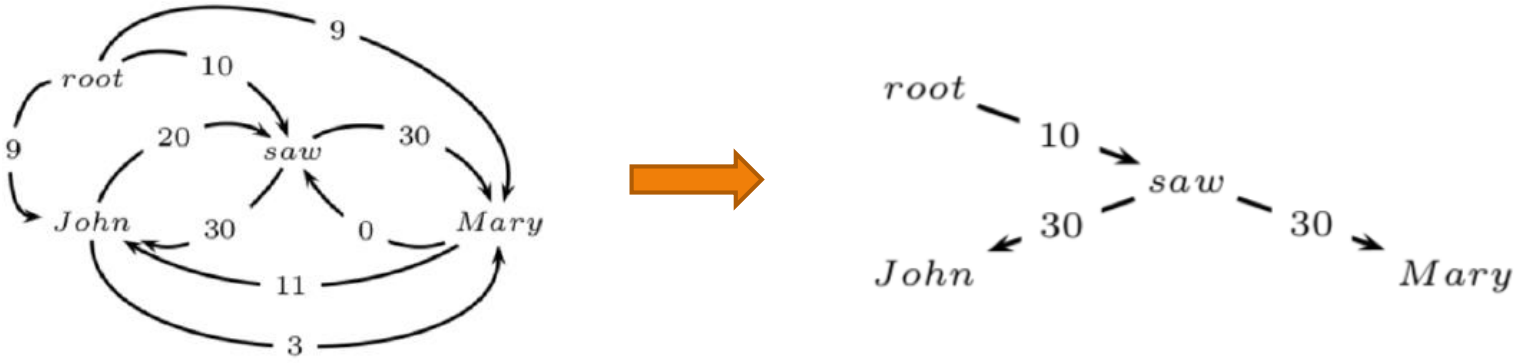
Graph-based parsing

- The tree score is the product of arc scores.



Graph-based parsing

- Parsing: find the highest-scoring parse tree
  - = max spanning directed tree (arborescence)
  - Solvable by greedy algorithm (Chu-Liu-Edmonds) and dynamic programming (Eisner)



Summary

- Constituency parsing
  - (Probabilistic) context-free grammars
  - CYK algorithm
- Regular grammars
- Dependency parsing