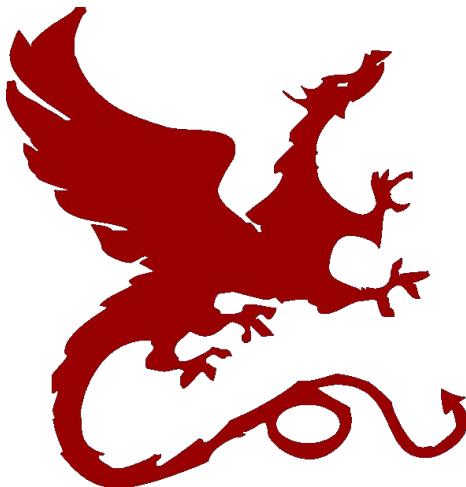


# Algorithms for NLP



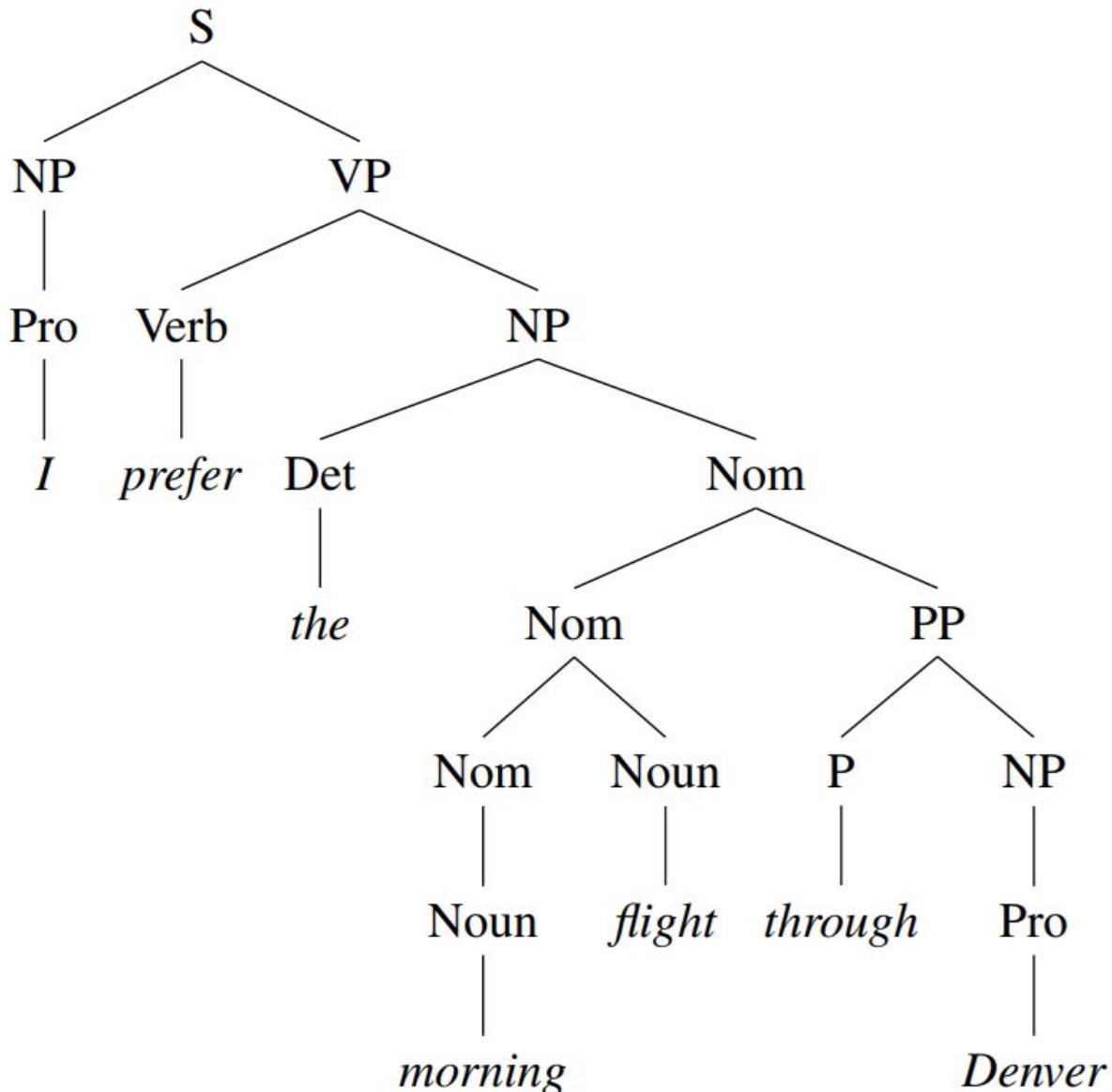
## Dependency Parsing

Yulia Tsvetkov – CMU

Slides: Images from Jurafsky & Martin 3rd ed. ch. 13

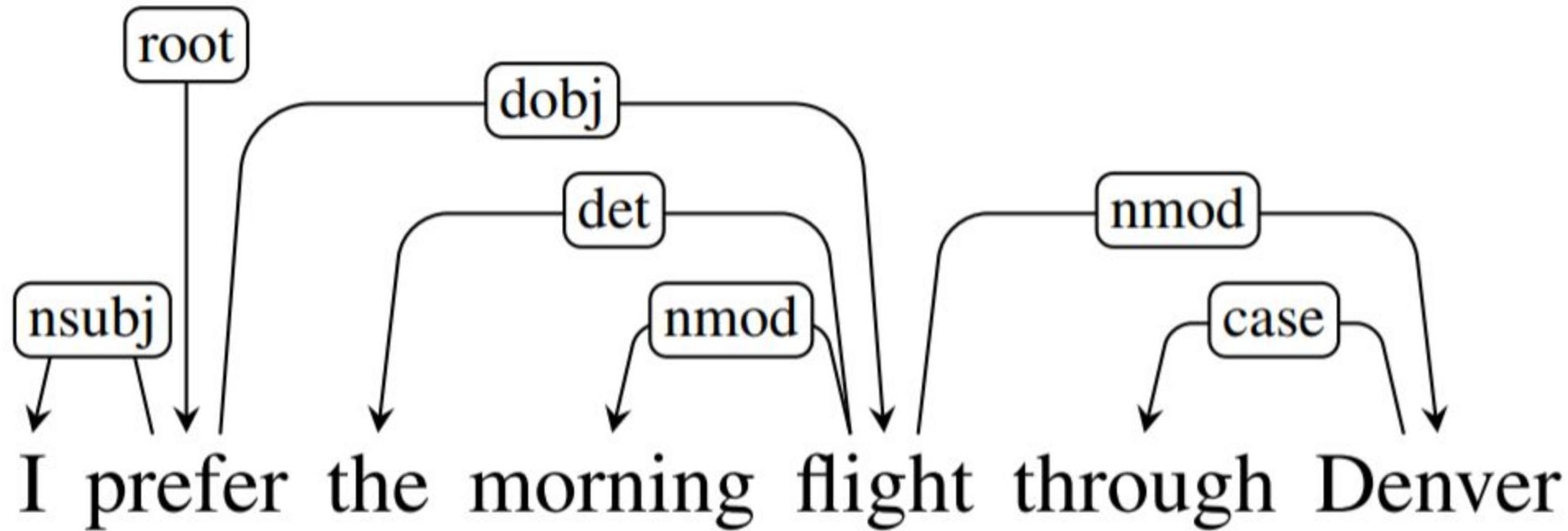


# Constituent (phrase-structure) representation



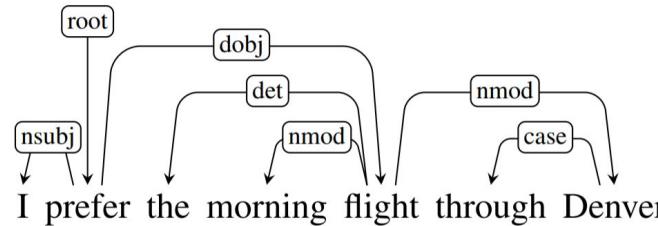


# Dependency representation





# Dependency representation



- A dependency structure can be defined as a directed graph  $G$ , consisting of
  - a set  $V$  of nodes – *vertices, words, punctuation, morphemes*
  - a set  $A$  of arcs – *directed edges,*
  - a linear precedence order  $<$  on  $V$  (*word order*).
- Labeled graphs
  - nodes in  $V$  are labeled with word forms (and annotation).
  - arcs in  $A$  are labeled with dependency types
  - $L = \{l_1, \dots, l_{|L|}\}$  is the set of permissible arc labels;
  - Every arc in  $A$  is a triple  $(i, j, k)$ , representing a dependency from  $w_i$  to  $w_j$  with label  $l_k$ .



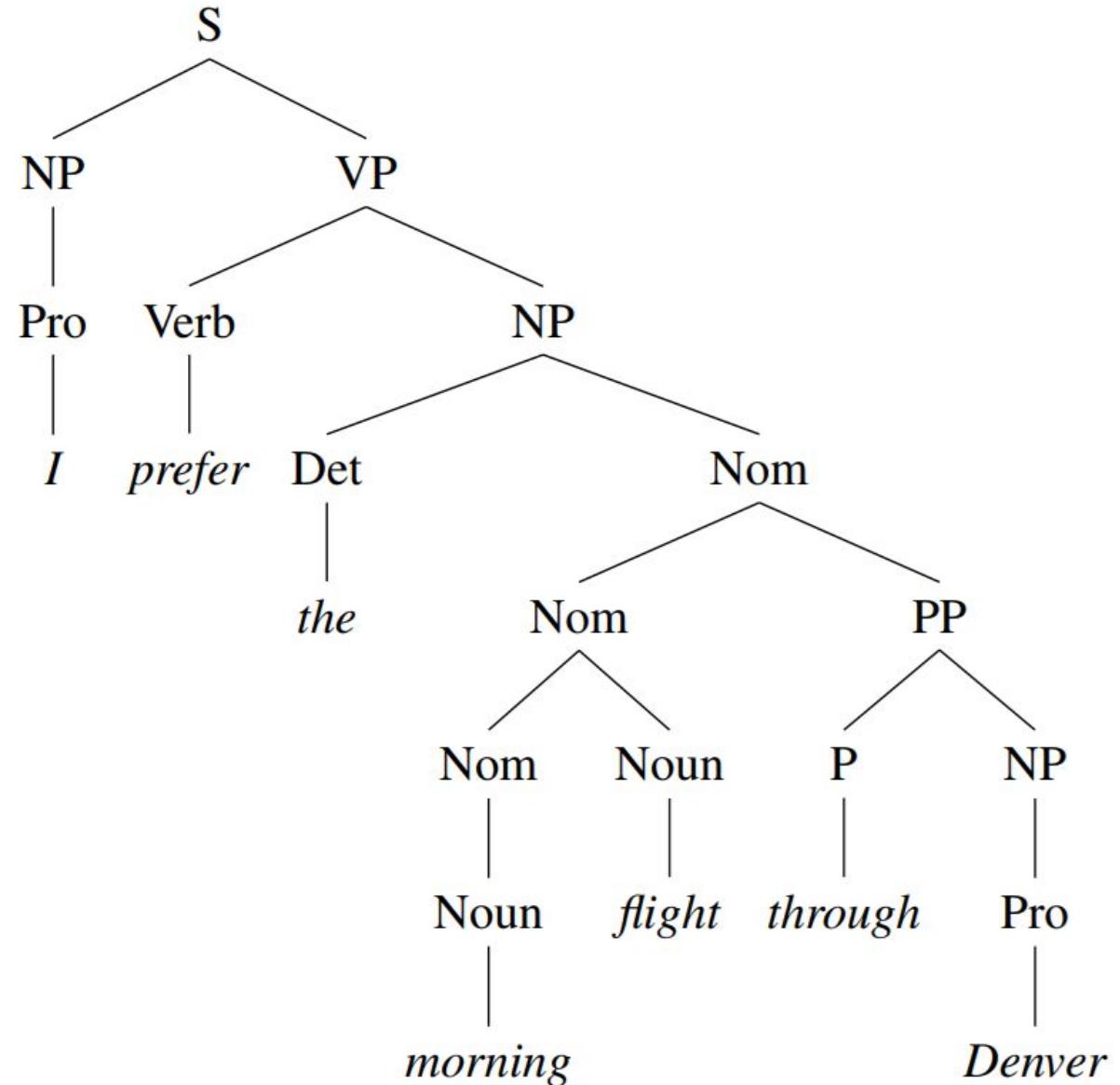
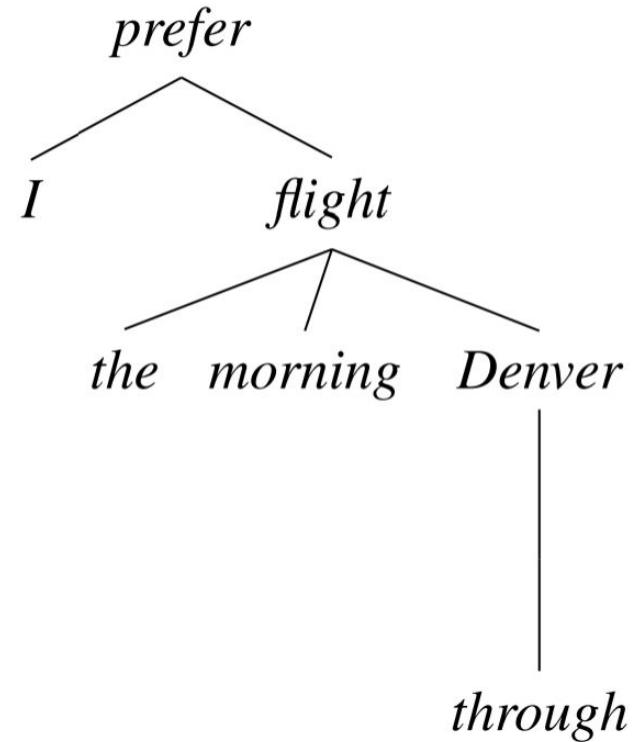
# Dependency vs Constituency

---

- Dependency structures explicitly represent
  - head-dependent relations (directed arcs),
  - functional categories (arc labels)
  - possibly some structural categories (parts of speech)
- Phrase (aka constituent) structures explicitly represent
  - phrases (nonterminal nodes),
  - structural categories (nonterminal labels)



# Dependency vs Constituency trees





# Parsing Languages with Flexible Word Order

---

I prefer the morning flight through Denver

Я предпочитаю утренний перелет через Денвер



# Languages with free word order

---

I prefer the morning flight through Denver

Я предпочитаю утренний перелет через Денвер

Я предпочитаю через Денвер утренний перелет

Утренний перелет я предпочитаю через Денвер

Перелет утренний я предпочитаю через Денвер

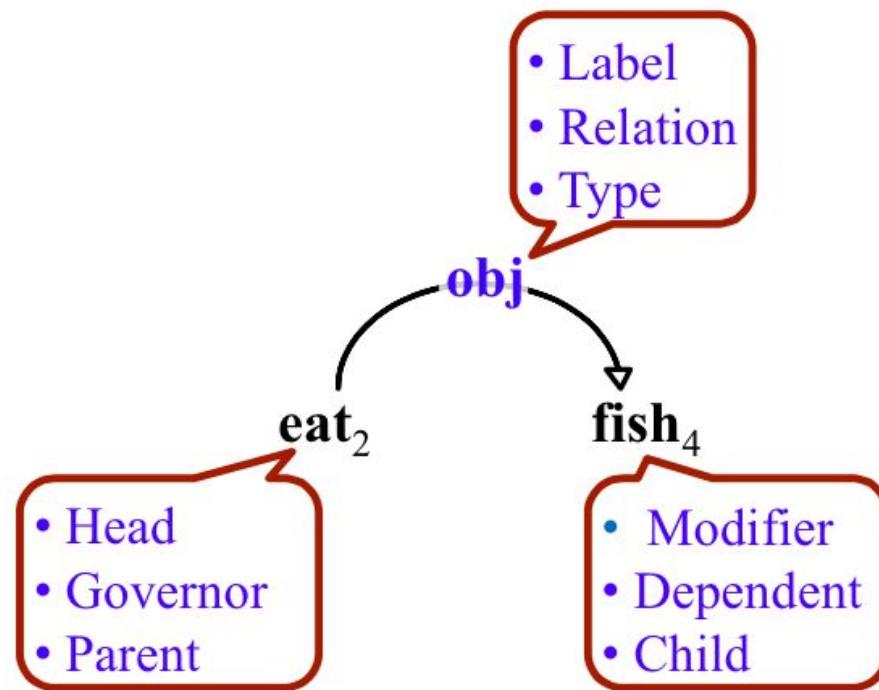
Через Денвер я предпочитаю утренний перелет

Я через Денвер предпочитаю утренний перелет



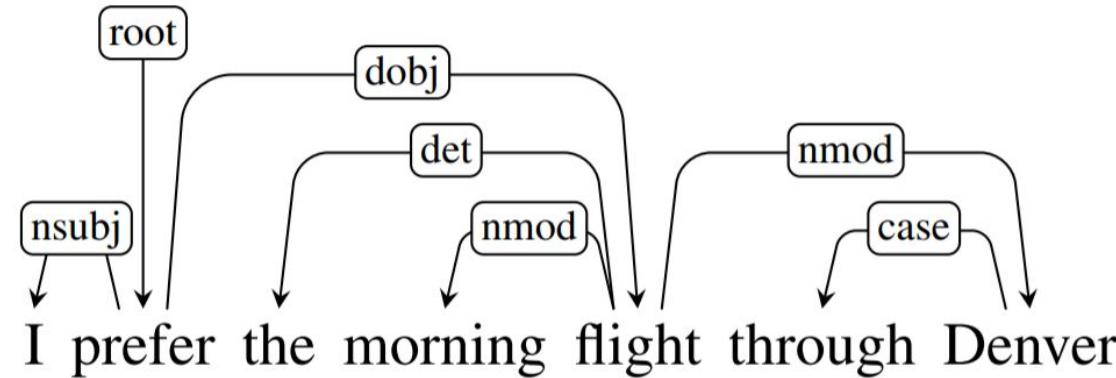
# Dependency relations

---





# Types of relationships



- The clausal relations NSUBJ and DOBJ identify the **arguments**: the subject and direct object of the predicate *cancel*
- The NMOD, DET, and CASE relations denote **modifiers** of the nouns *flights* and *Houston*.



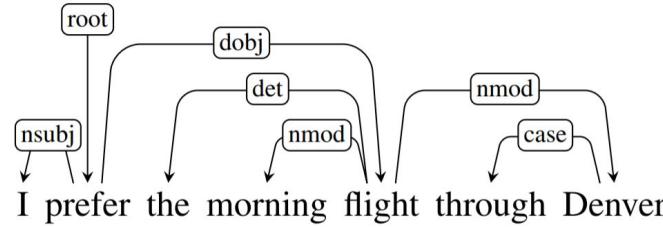
# Grammatical functions

Clausal Argument Relations	Description
NSUBJ	Nominal subject
DOBJ	Direct object
IOBJ	Indirect object
CCOMP	Clausal complement
XCOMP	Open clausal complement
Nominal Modifier Relations	Description
NMOD	Nominal modifier
AMOD	Adjectival modifier
NUMMOD	Numeric modifier
APPOS	Appositional modifier
DET	Determiner
CASE	Prepositions, postpositions and other case markers
Other Notable Relations	Description
CONJ	Conjunct
CC	Coordinating conjunction

**Figure 13.2** Selected dependency relations from the Universal Dependency set. (de Marn-  
effe et al., 2014)



# Dependency Constraints



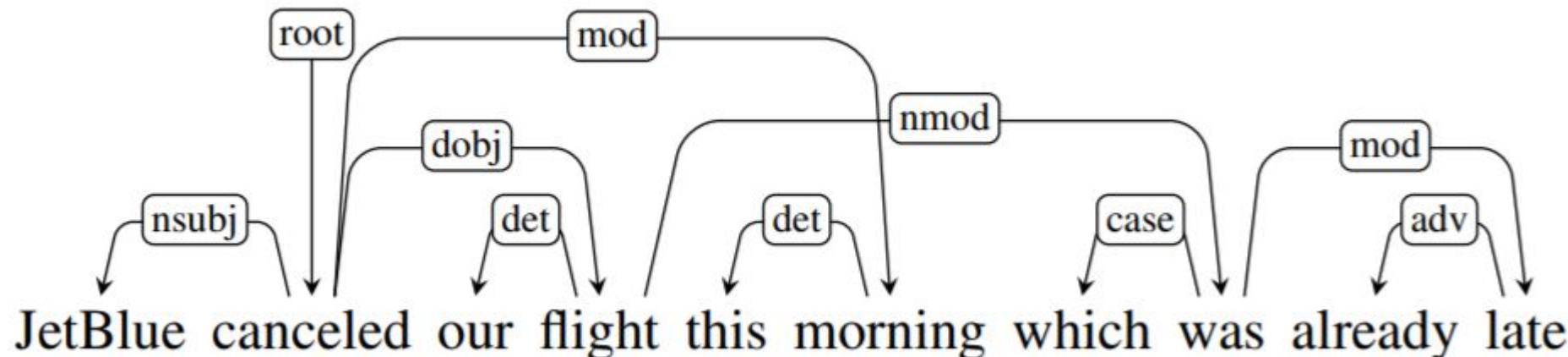
- Syntactic structure is complete (**connectedness**)
  - connectedness can be enforced by adding a special root node
- Syntactic structure is hierarchical (**acyclicity**)
  - there is a unique pass from the root to each vertex
- Every word has at most one syntactic head (**single-head constraint**)
  - except root that does not have incoming arcs

This makes the dependencies a tree



# Projectivity

- Projective parse
  - arcs don't cross each other
  - mostly true for English
- Non-projective structures are needed to account for
  - long-distance dependencies
  - flexible word order





# Projectivity

---

- Dependency grammars do not normally assume that all dependency-trees are projective, because some linguistic phenomena can only be achieved using non-projective trees.
- But a lot of parsers assume that the output trees are projective
- Reasons
  - conversion from constituency to dependency
  - the most widely used families of parsing algorithms impose projectivity



# Detecting Projectivity/Non-Projectivity

---

- The idea is to use the inorder traversal of the tree: <left-child, root, right-child>
  - This is well defined for binary trees. We need to extend it to n-ary trees.
- If we have a projective tree, the inorder traversal will give us the original linear order.



# Non-Projective Statistics

---

Arabic: 11.2 %

Bulgarian: 5.4 %

Chinese: 0.0 %

**Czech: 23.2 %**

**Danish: 15.6 %**

**Dutch: 36.4 %**

**German: 27.8 %**

Japanese: 5.3 %

**Polish: 18.9 %**

**Slovene: 22.2 %**

Spanish 1.7 %

Swedish: 9.8 %

Turkish: 11.6 %

English: 0.0% (SD: 0.1%)



# Conversion from constituency to dependency

- Xia and Palmer (2001)
  - mark the head child of each node in a phrase structure, using the appropriate head rules
  - make the head of each non-head child depend on the head of the head-child

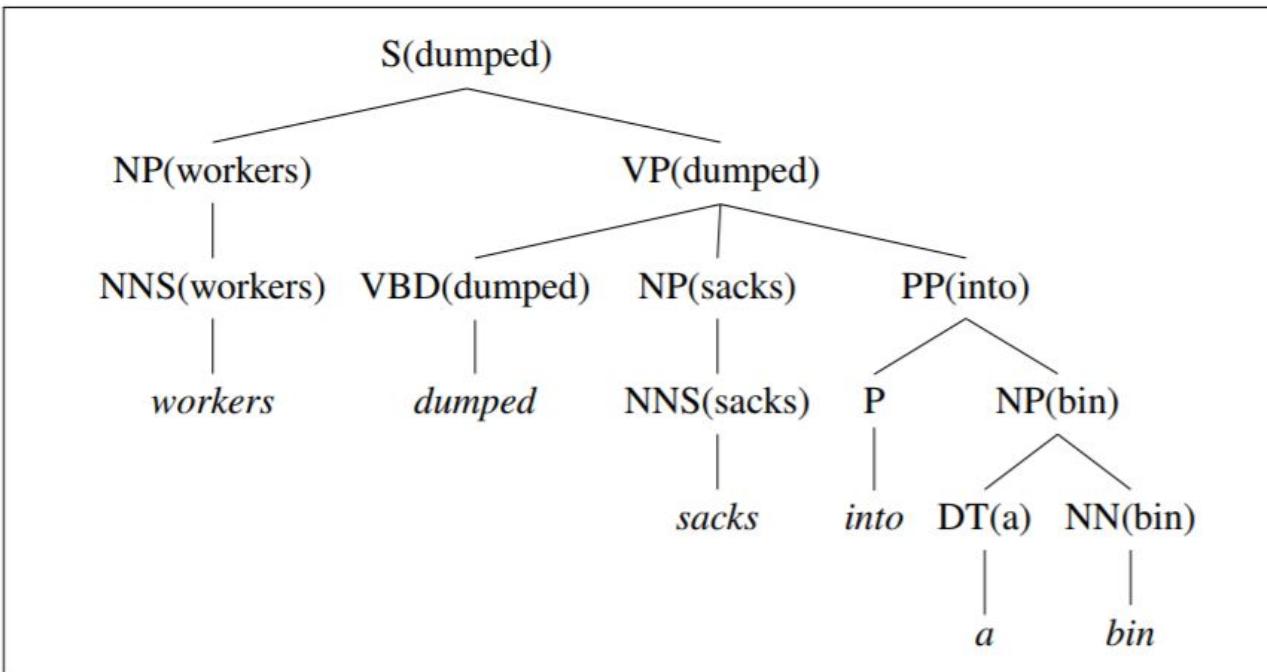


Figure 10.11 A lexicalized tree from Collins (1999).



# Dependency Treebanks

---

- the major English dependency treebanks converted from the WSJ sections of the PTB (Marcus et al., 1993)
- OntoNotes project (Hovy et al. 2006, Weischedel et al. 2011) adds conversational telephone speech, weblogs, usenet newsgroups, broadcast, and talk shows in English, Chinese and Arabic
- annotated dependency treebanks created for morphologically rich languages such as Czech, Hindi and Finnish, eg Prague Dependency Treebank (Bejcek et al., 2013)
- <http://universaldependencies.org/>
  - 122 treebanks, 71 languages



# Parsing problem

---

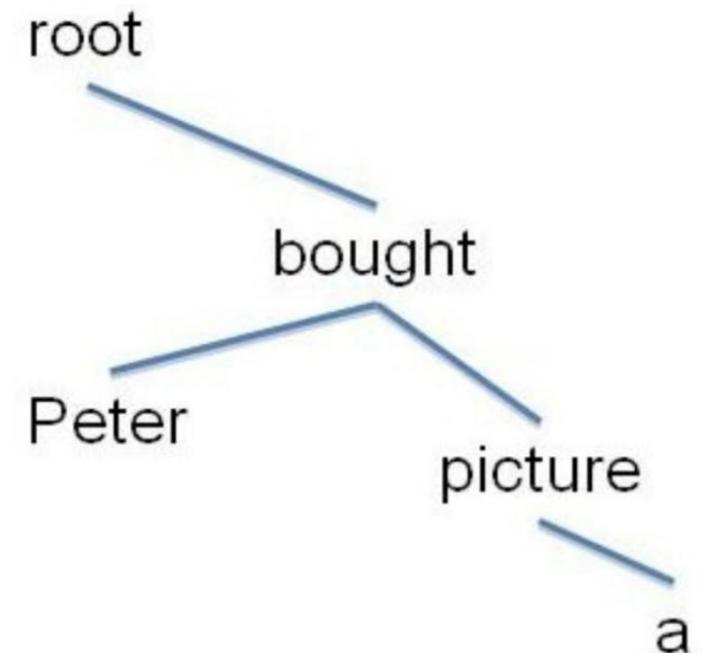
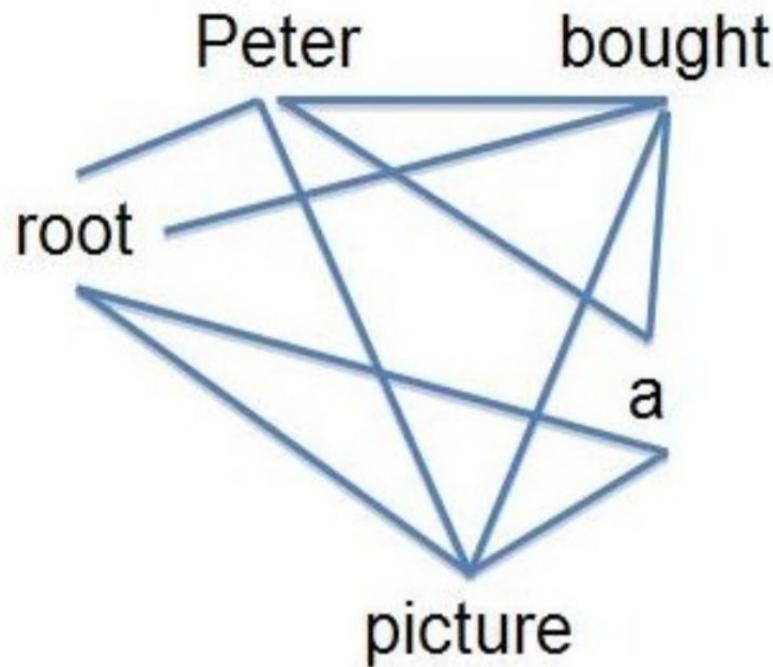
The parsing problem for a dependency parser is to find the optimal dependency tree  $y$  given an input sentence  $x$

This amounts to assigning a syntactic head  $i$  and a label  $l$  to every node  $j$  corresponding to a word  $x_j$ , in such a way that the resulting graph is a tree rooted at the node 0



# Parsing problem

- This is equivalent to finding a spanning tree in the complete graph containing all possible arcs





# Parsing algorithms

---

- Transition based
  - greedy choice of local transitions guided by a good classifier
  - deterministic
  - MaltParser (Nivre et al. 2008)
- Graph based
  - Minimum Spanning Tree for a sentence
  - McDonald et al.'s (2005) MSTParser
  - Martins et al.'s (2009) Turbo Parser



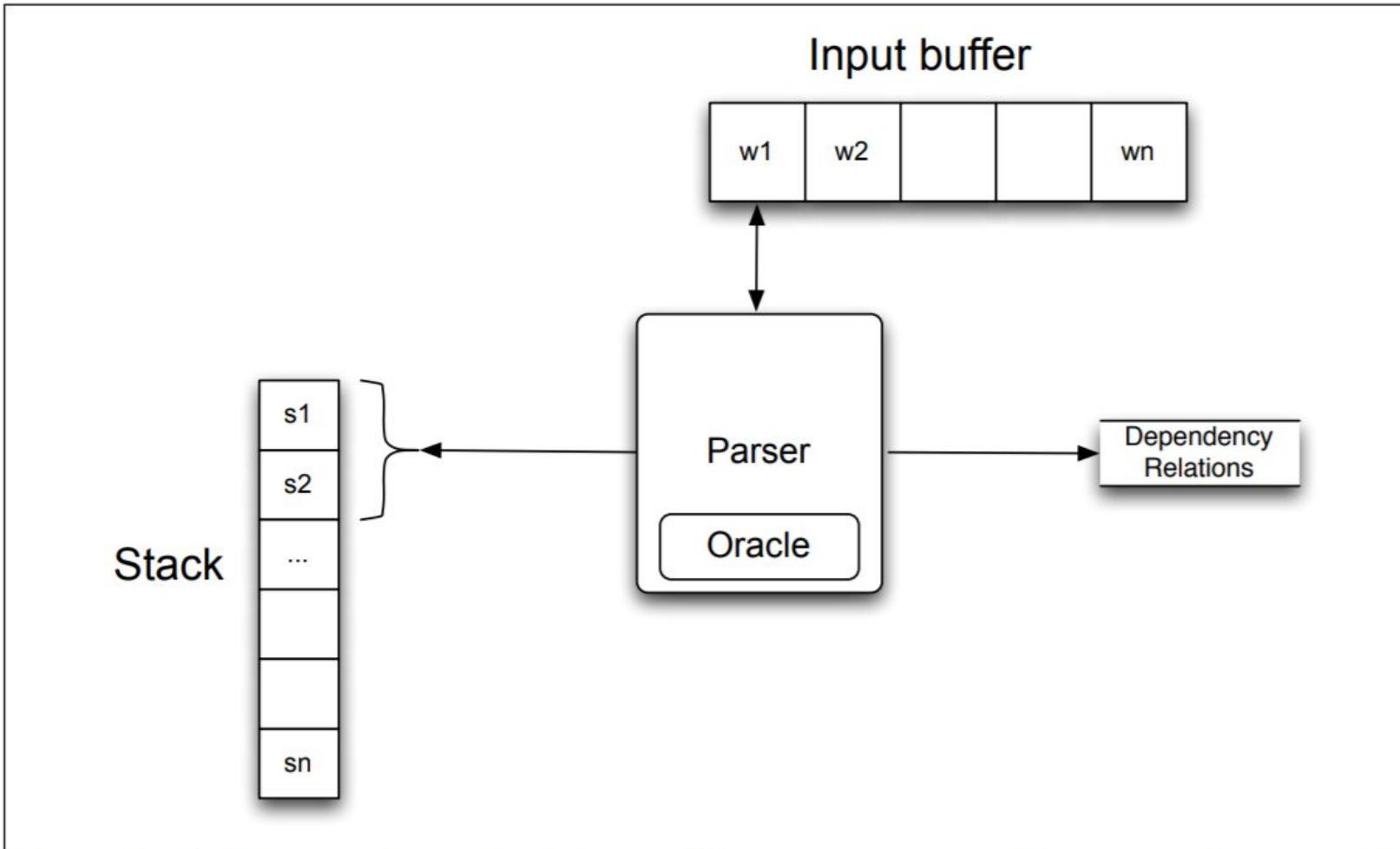
# Transition Based Parsing

---

- greedy discriminative dependency parser
- motivated by a stack-based approach called **shift-reduce parsing** originally developed for analyzing programming languages (Aho & Ullman, 1972).
- Nivre 2003



# Configuration



**Figure 13.5** Basic transition-based parser. The parser examines the top two elements of the stack and selects an action based on consulting an oracle that examines the current configuration.



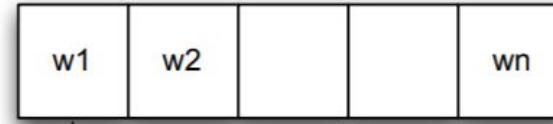
# Configuration

**Stack:** partially processed words

Stack



Input buffer



**Buffer:** unprocessed words

**Oracle:** a classifier





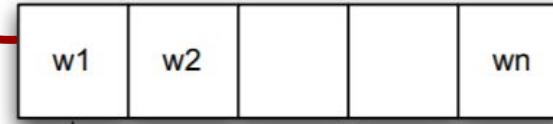
# Operations

**Stack:** partially processed words

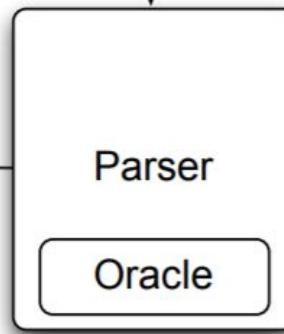
Stack



Input buffer



**Buffer:** unprocessed words



Dependency  
Relations

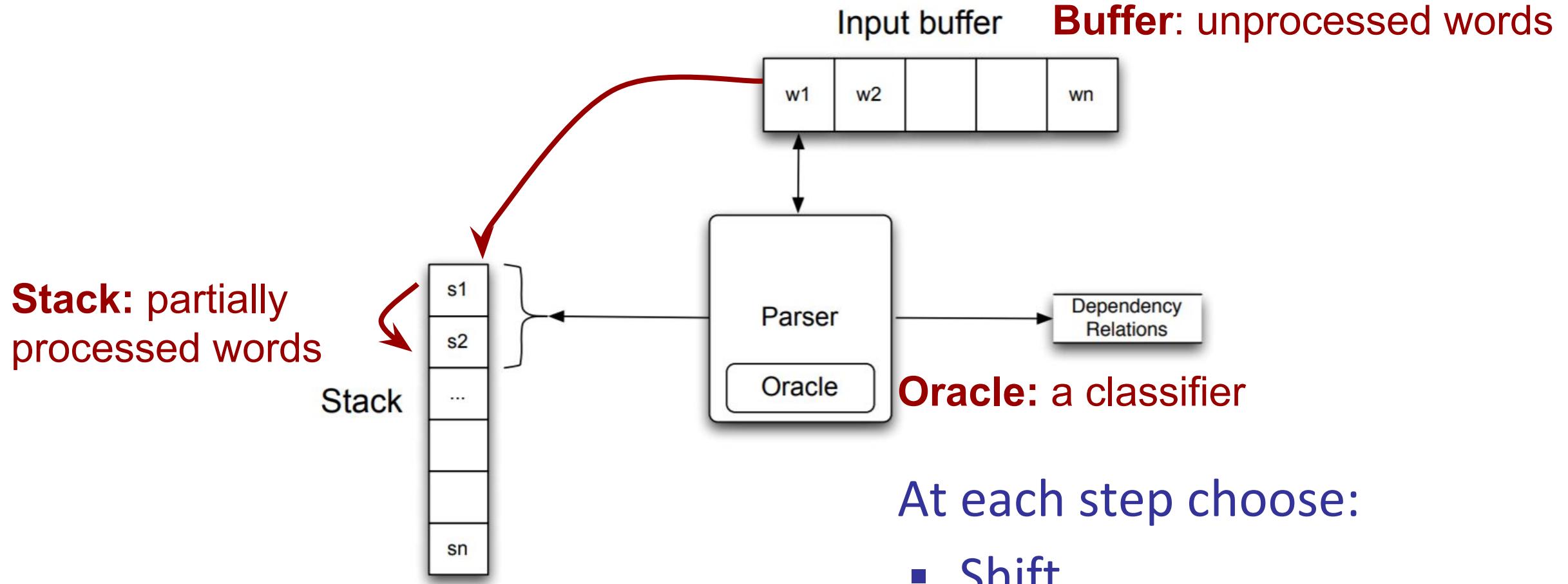
**Oracle:** a classifier

At each step choose:

- Shift



# Operations

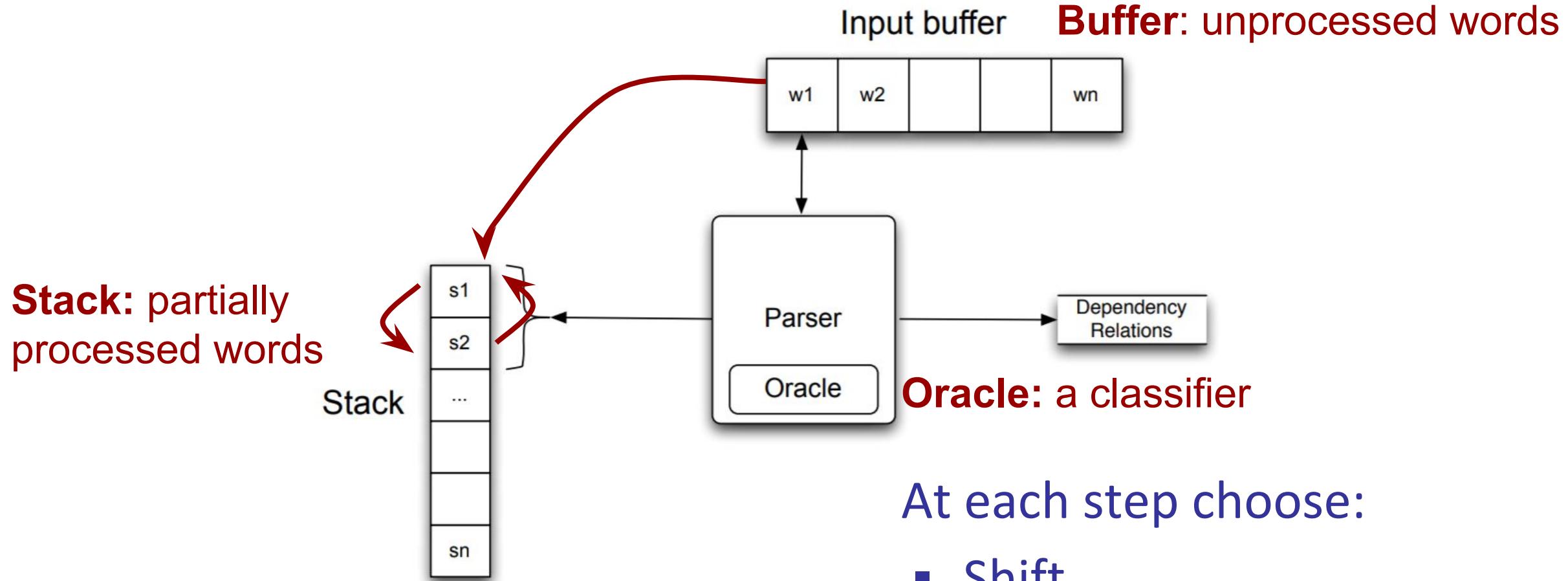


At each step choose:

- Shift
- Reduce left



# Operations



At each step choose:

- Shift
- LeftArc or Reduce left
- RightArc or Reduce right



# Shift-Reduce Parsing

---

Configuration:

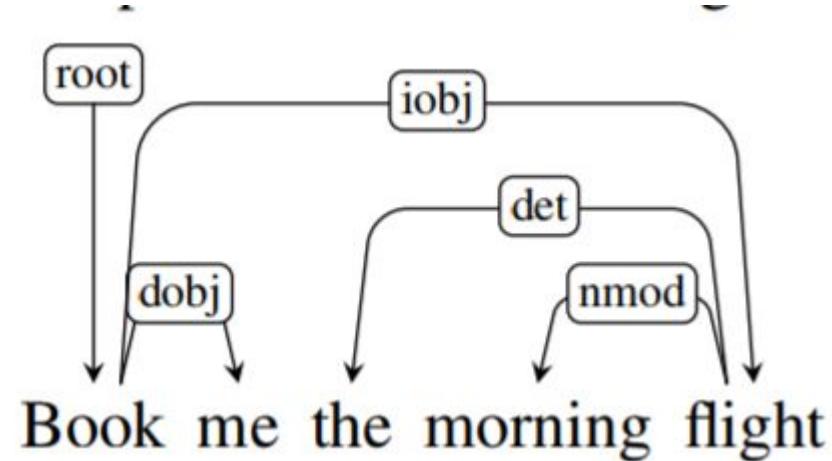
- Stack, Buffer, Oracle, Set of dependency relations

Operations by a classifier at each step:

- Shift
  - remove w1 from the buffer, add it to the top of the stack as s1
- LeftArc or Reduce left
  - assert a head-dependent relation between s1 and s2
  - remove s2 from the stack
- RightArc or Reduce right
  - assert a head-dependent relation between s2 and s1
  - remove s1 from the stack



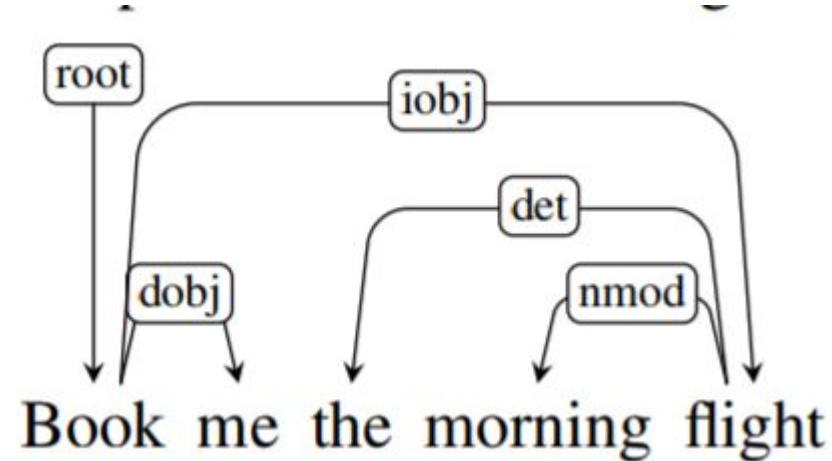
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	



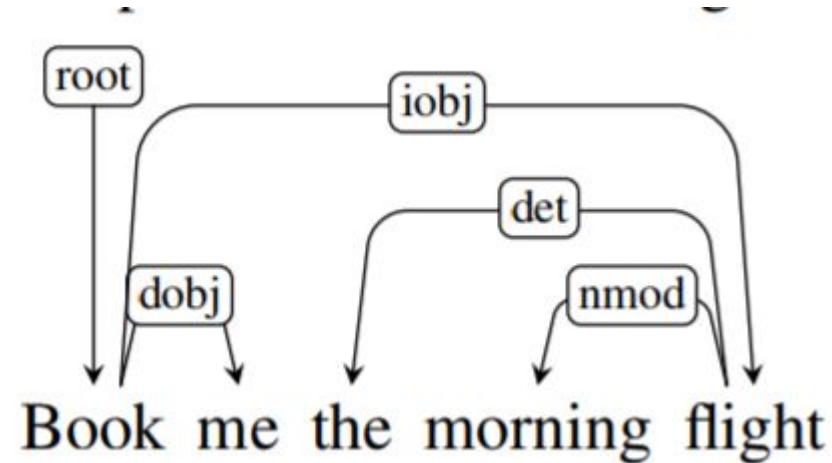
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	



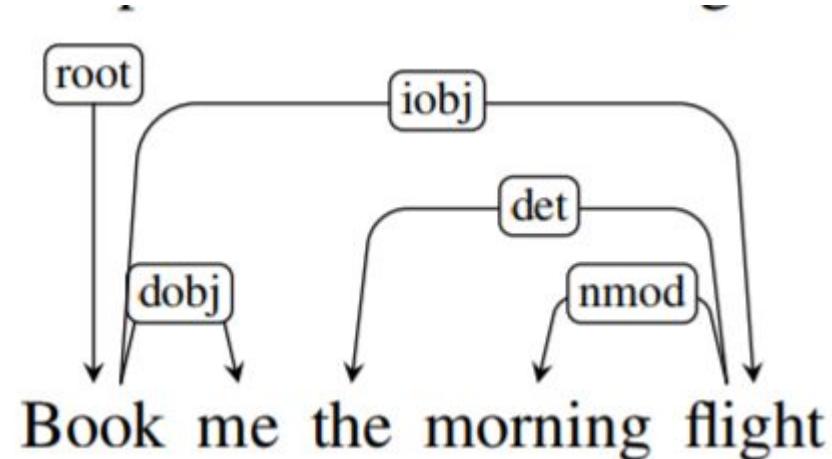
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]		



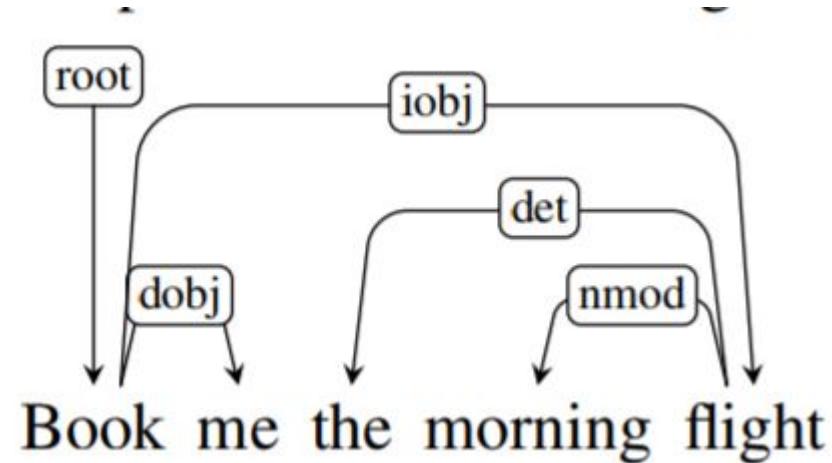
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)



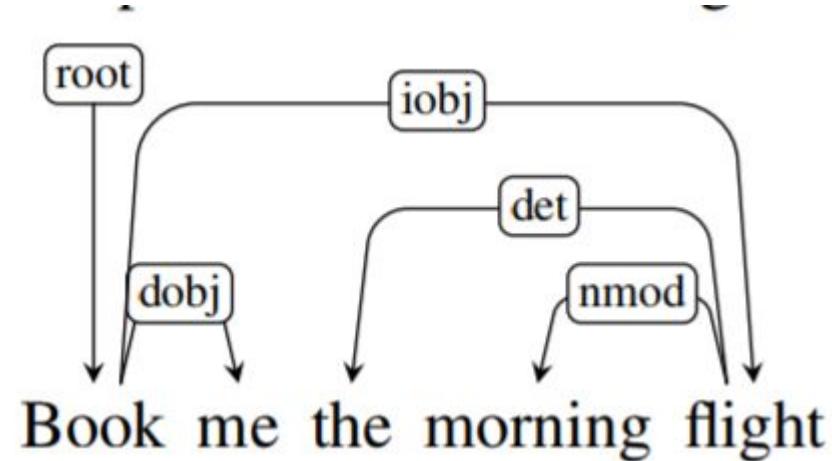
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	



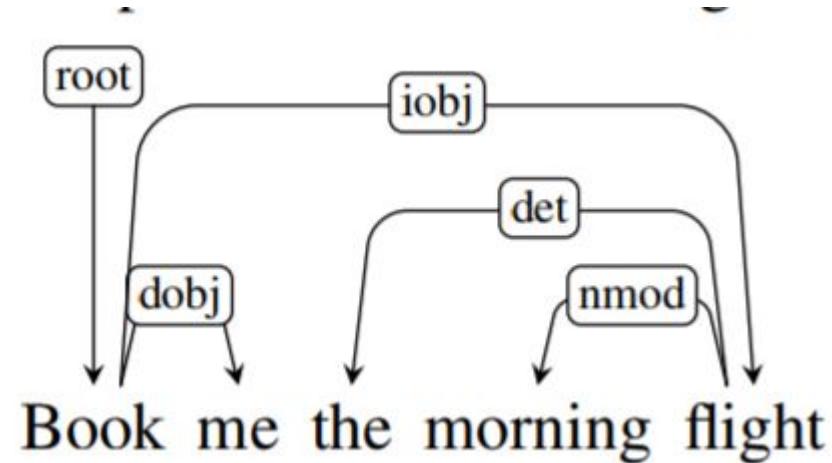
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	



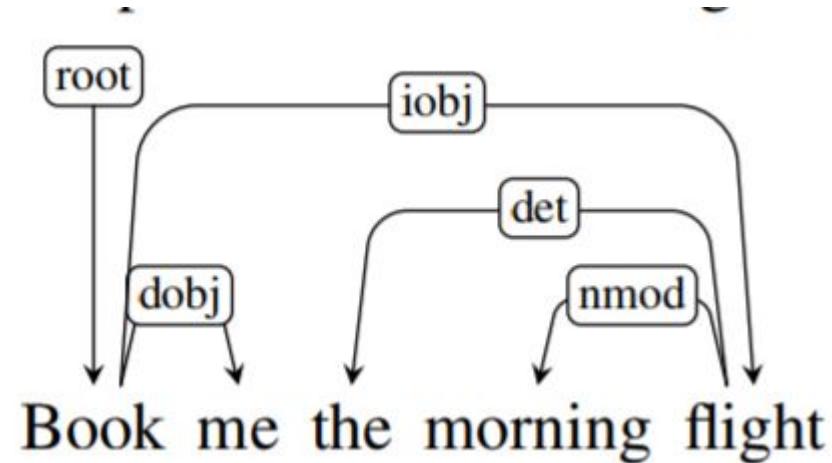
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root, book, the, morning]	[flight]	SHIFT	



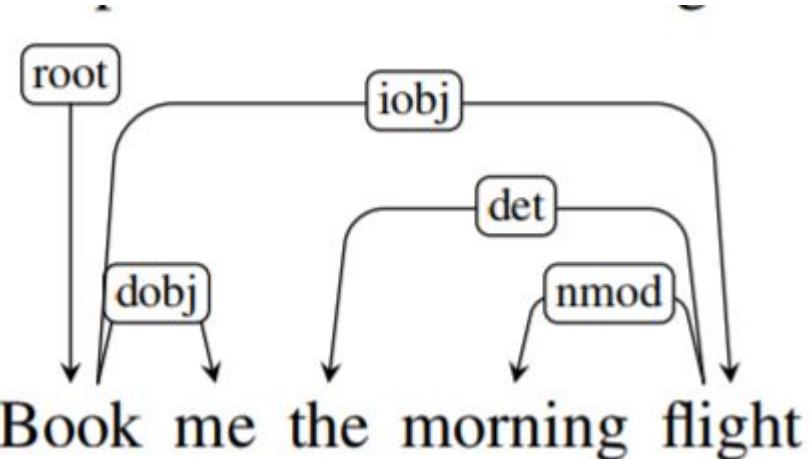
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root, book, the, morning]	[flight]	SHIFT	
6	[root, book, the, morning, flight]	[]	LEFTARC	(morning ← flight)



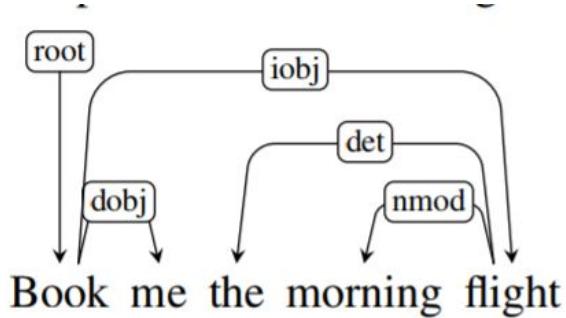
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root, book, the, morning]	[flight]	SHIFT	
6	[root, book, the, morning, flight]	[]	LEFTARC	(morning ← flight)
7	[root, book, the, flight]	[]	LEFTARC	(the ← flight)



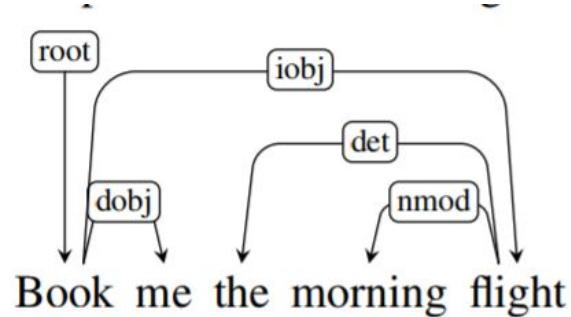
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root, book, the, morning]	[flight]	SHIFT	
6	[root, book, the, morning, flight]	[]	LEFTARC	(morning ← flight)
7	[root, book, the, flight]	[]	LEFTARC	(the ← flight)
8	[root, book, flight]	[]	RIGHTARC	(book → flight)



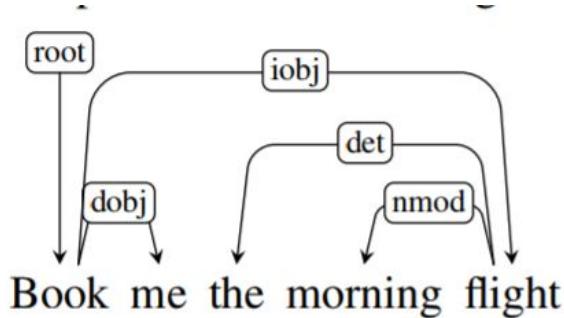
# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root, book, the, morning]	[flight]	SHIFT	
6	[root, book, the, morning, flight]	[]	LEFTARC	(morning ← flight)
7	[root, book, the, flight]	[]	LEFTARC	(the ← flight)
8	[root, book, flight]	[]	RIGHTARC	(book → flight)
9	[root, book]	[]	RIGHTARC	(root → book)



# Shift-Reduce Parsing



Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root, book, the, morning]	[flight]	SHIFT	
6	[root, book, the, morning, flight]	[]	LEFTARC	(morning ← flight)
7	[root, book, the, flight]	[]	LEFTARC	(the ← flight)
8	[root, book, flight]	[]	RIGHTARC	(book → flight)
9	[root, book]	[]	RIGHTARC	(root → book)
10	[root]	[]	Done	



# Shift-Reduce Parsing

Configuration:

- Stack, Buffer, Oracle, Set of dependency relations

Operations by a classifier at each step:

Complexity?

- Shift
  - remove  $w_1$  from the buffer, add it to the top of the stack as  $s_1$
- LeftArc or Reduce left
  - assert a head-dependent relation between  $s_2$  and  $s_1$
  - remove  $s_2$  from the stack
- RightArc or Reduce right
  - assert a head-dependent relation between  $s_2$  and  $s_1$
  - remove  $s_1$  from the stack

Oracle decisions can correspond to unlabeled or labeled arcs



# Training an Oracle

---

- Oracle is a supervised classifier that learns a function from the configuration to the next operation
- How to extract the training set?



# Training an Oracle

---

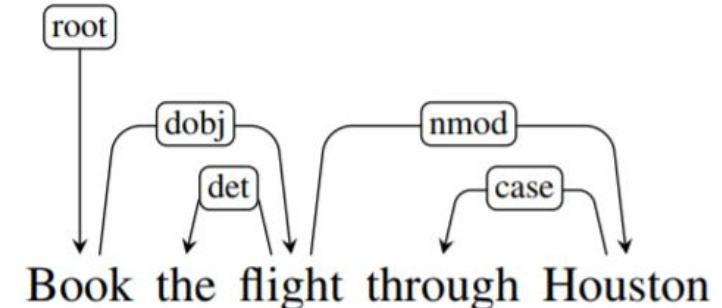
- How to extract the training set?
  - if LeftArc → LeftArc
  - if RightArc
    - if s1 dependents have been processed → RightArc
  - else → Shift



# Training an Oracle

- How to extract the training set?

- if LeftArc → LeftArc
- if RightArc
  - if s1 dependents have been processed → RightArc
- else → Shift



Step	Stack	Word List	Predicted Action
0	[root]	[book, the, flight, through, houston]	SHIFT
1	[root, book]	[the, flight, through, houston]	SHIFT
2	[root, book, the]	[flight, through, houston]	SHIFT
3	[root, book, the, flight]	[through, houston]	LEFTARC
4	→ [root, book, flight]	[through, houston]	SHIFT
5	[root, book, flight, through]	[houston]	SHIFT
6	[root, book, flight, through, houston]	[]	LEFTARC
7	[root, book, flight, houston ]	[]	RIGHTARC
8	[root, book, flight]	[]	RIGHTARC
9	[root, book]	[]	RIGHTARC



# Training an Oracle

---

- Oracle is a supervised classifier that learns a function from the configuration to the next operation
- How to extract the training set?
  - if LeftArc → LeftArc
  - if RightArc
    - if s1 dependents have been processed → RightArc
  - else → Shift
- What features to use?



# Features

- POS, word-forms, lemmas on the stack/buffer       $\langle s_1.w = flights, op = shift \rangle$
- morphological features for some languages       $\langle s_2.w = canceled, op = shift \rangle$
- previous relations       $\langle s_1.t = NNS, op = shift \rangle$
- conjunction features (e.g. Zhang&Clark'08;  
Huang&Sagae'10; Zhang&Nivre'11)       $\langle s_2.t = VBD, op = shift \rangle$   
     $\langle b_1.w = to, op = shift \rangle$   
     $\langle b_1.t = TO, op = shift \rangle$   
     $\langle s_1.wt = flightsNNS, op = shift \rangle$   
     $\langle s_1.t \circ s_2.t = NNSVBD, op = shift \rangle$

Source	Feature templates		
<b>One word</b>	$s_1.w$	$s_1.t$	$s_1.wt$
	$s_2.w$	$s_2.t$	$s_2.wt$
	$b_1.w$	$b_1.w$	$b_0.wt$
<b>Two word</b>	$s_1.w \circ s_2.w$	$s_1.t \circ s_2.t$	$s_1.t \circ b_1.w$
	$s_1.t \circ s_2.wt$	$s_1.w \circ s_2.w \circ s_2.t$	$s_1.w \circ s_1.t \circ s_2.t$
	$s_1.w \circ s_1.t \circ s_2.t$	$s_1.w \circ s_1.t$	



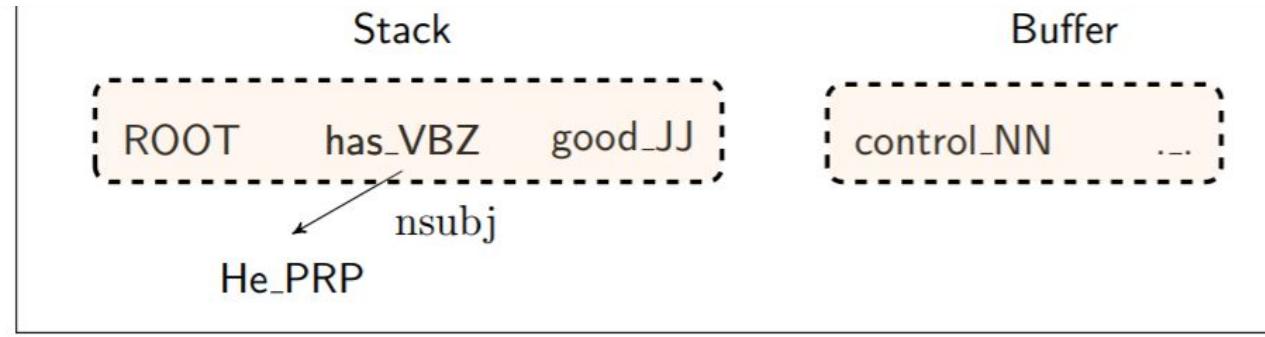
# Learning

---

- Before 2014: SVMs,
- After 2014: Neural Nets



# Chen & Manning 2014



binary, sparse  
dim =  $10^6 \sim 10^7$



Indicator  
features

$s_2.w = \text{has} \wedge s_2.t = \text{VBZ}$   
 $s_1.w = \text{good} \wedge s_1.t = \text{JJ} \wedge b_1.w = \text{control}$   
 $lc(s_2).t = \text{PRP} \wedge s_2.t = \text{VBZ} \wedge s_1.t = \text{JJ}$   
 $lc(s_2).w = \text{He} \wedge lc(s_2).l = \text{nsubj} \wedge s_2.w = \text{has}$



## Softmax probabilities

Output layer  $y$

$$y = \text{softmax}(Uh + b_2)$$

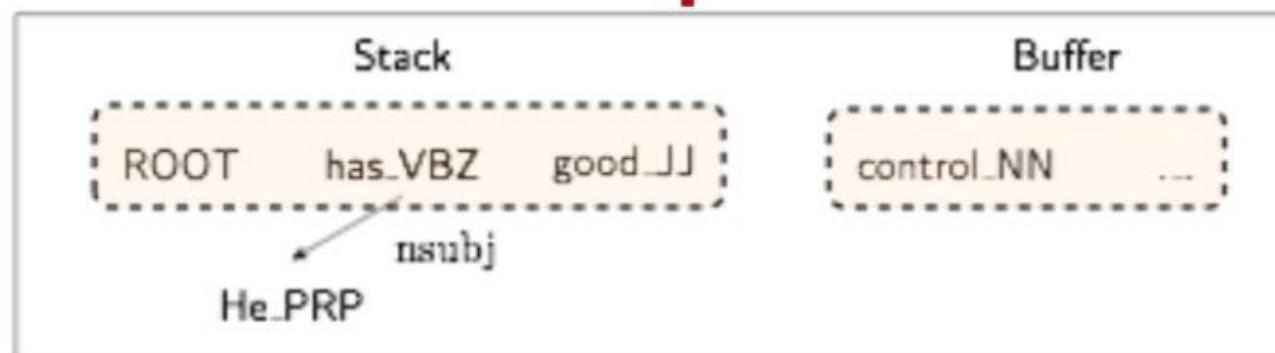
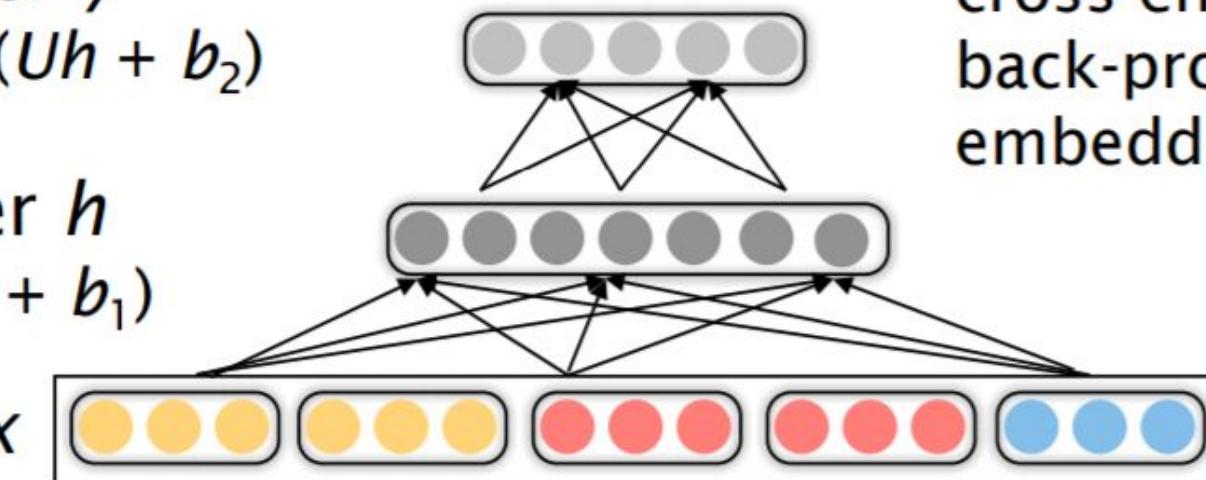
Hidden layer  $h$

$$h = \text{ReLU}(Wx + b_1)$$

Input layer  $x$

lookup + concat

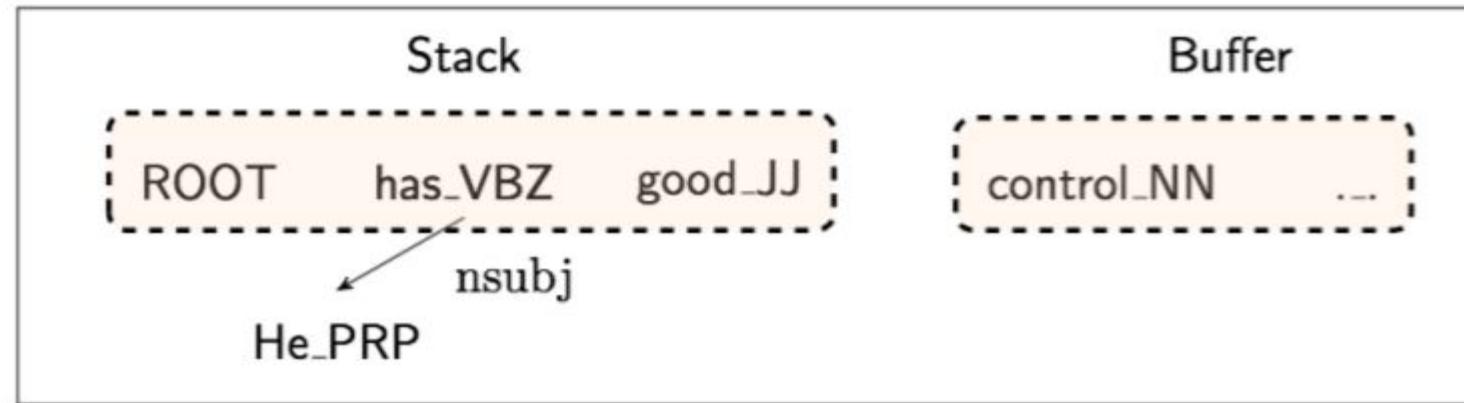
cross-entropy error will be back-propagated to the embeddings.





## Features

- $s_1, s_2, s_3, b_1, b_2, b_3$
- leftmost/rightmost children of  $s_1$  and  $s_2$
- leftmost/rightmost grandchildren of  $s_1$  and  $s_2$
- POS tags for the above
- arc labels for children/grandchildren



	word	POS	dep.
$s_1$	good	JJ	$\emptyset$
$s_2$	has	VBZ	$\emptyset$
$b_1$	control	NN	$\emptyset$
$lc(s_1)$	∅	∅	+
$rc(s_1)$	∅	∅	+
$lc(s_2)$	He	PRP	$nsubj$
$rc(s_2)$	∅	∅	$\emptyset$



# Evaluation of Dependency Parsers

---

$$\frac{\# \text{correct dependencies}}{\# \text{of dependencies}}$$

- LAS - labeled attachment score
- UAS - unlabeled attachment score



# Chen & Manning 2014

Parser	UAS	LAS	sent. / s
MaltParser	89.8	87.2	469
MSTParser	91.4	88.1	10
TurboParser	<b>92.3*</b>	89.6*	8
C & M 2014	92.0	<b>89.7</b>	<b>654</b>



# Follow-up

---

Method	UAS	LAS (PTB WSJ SD 3.3)
Chen & Manning 2014	92.0	89.7
Weiss et al. 2015	93.99	92.05
Andor et al. 2016	94.61	92.79



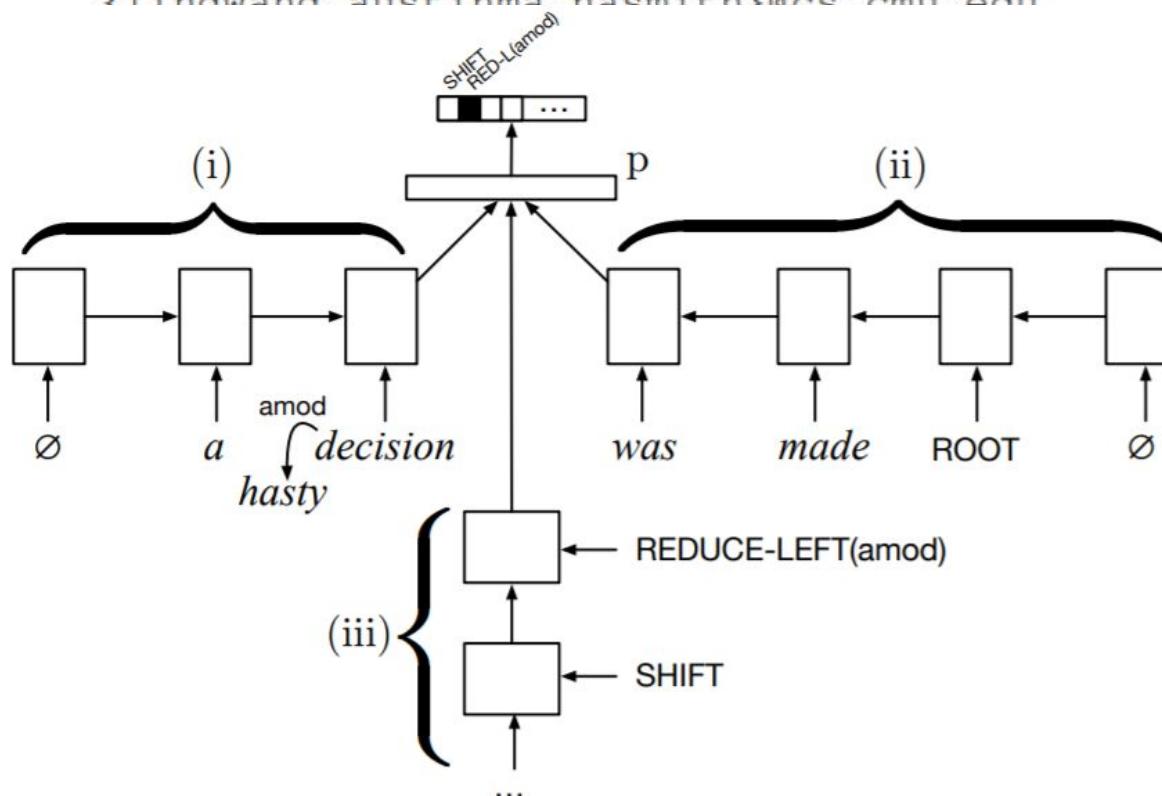
# Stack LSTMs (Dyer et al. 2015)

## Transition-Based Dependency Parsing with Stack Long Short-Term Memory

Chris Dyer<sup>♦♦</sup> Miguel Ballesteros<sup>◊♣</sup> Wang Ling<sup>♣</sup> Austin Matthews<sup>♣</sup> Noah A. Smith<sup>♣</sup>

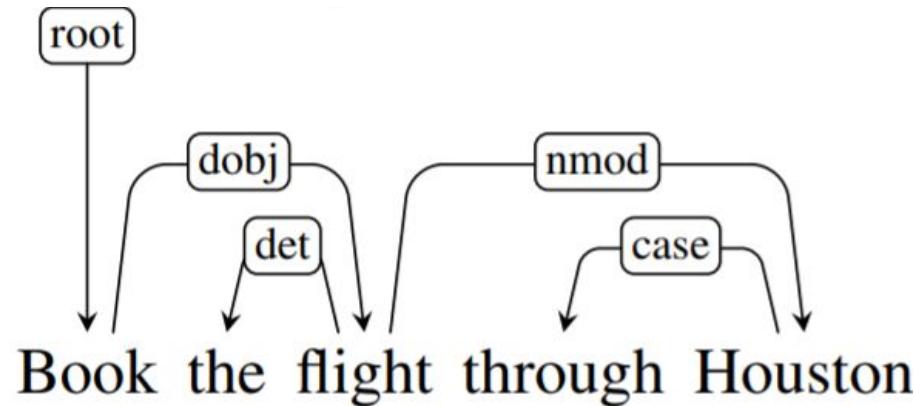
<sup>♦</sup>Marianas Labs   <sup>◊</sup>NLP Group, Pompeu Fabra University   <sup>♣</sup>Carnegie Mellon University

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flingwang.austinma.noahsmith@cs.cmu.edu





# Arc-Eager



- LEFTARC: Assert a head-dependent relation between s<sub>1</sub> and b<sub>1</sub>; pop the stack.
- RIGHTARC: Assert a head-dependent relation between s<sub>1</sub> and b<sub>1</sub>; shift b<sub>1</sub> to be s<sub>1</sub>.
- SHIFT: Remove b<sub>1</sub> and push it to be s<sub>1</sub>.
- REDUCE: Pop the stack.



# Arc-Eager

Step	Stack	Word List	Action	Relation Added
0	[root]	[book, the, flight, through, houston]	RIGHTARC	(root → book)
1	[root, book]	[the, flight, through, houston]	SHIFT	
2	[root, book, the]	[flight, through, houston]	LEFTARC	(the ← flight)
3	[root, book]	[flight, through, houston]	RIGHTARC	(book → flight)
4	[root, book, flight]	[through, houston]	SHIFT	
5	[root, book, flight, through]	[houston]	LEFTARC	(through ← houston)
6	[root, book, flight]	[houston]	RIGHTARC	(flight → houston)
7	[root, book, flight, houston]	[]	REDUCE	
8	[root, book, flight]	[]	REDUCE	
9	[root, book]	[]	REDUCE	
10	[root]	[]	Done	



# Beam Search

---

**function** DEPENDENCYBEAMPARSE(*words*, *width*) **returns** dependency tree

*state*  $\leftarrow \{[\text{root}], [\text{words}], [], 0.0\}$  ;initial configuration

*agenda*  $\leftarrow \langle \text{state} \rangle$ ; initial agenda

**while** *agenda* contains non-final states

*newagenda*  $\leftarrow \langle \rangle$

**for each** *state*  $\in$  *agenda* **do**

**for all**  $\{t \mid t \in \text{VALIDOPERATORS}(state)\}$  **do**

*child*  $\leftarrow \text{APPLY}(t, state)$

*newagenda*  $\leftarrow \text{ADDTOBEAM}(\text{child}, \text{newagenda}, width)$

*agenda*  $\leftarrow \text{newagenda}$

**return** **BESTOF**(*agenda*)

**function** ADDTOBEAM(*state*, *agenda*, *width*) **returns** updated agenda

**if** LENGTH(*agenda*)  $<$  *width* **then**

*agenda*  $\leftarrow \text{INSERT}(\text{state}, \text{agenda})$

**else if** SCORE(*state*)  $>$  SCORE(WORSTOF(*agenda*))

*agenda*  $\leftarrow \text{REMOVE}(\text{WORSTOF}(\text{agenda}))$

*agenda*  $\leftarrow \text{INSERT}(\text{state}, \text{agenda})$

**return** *agenda*



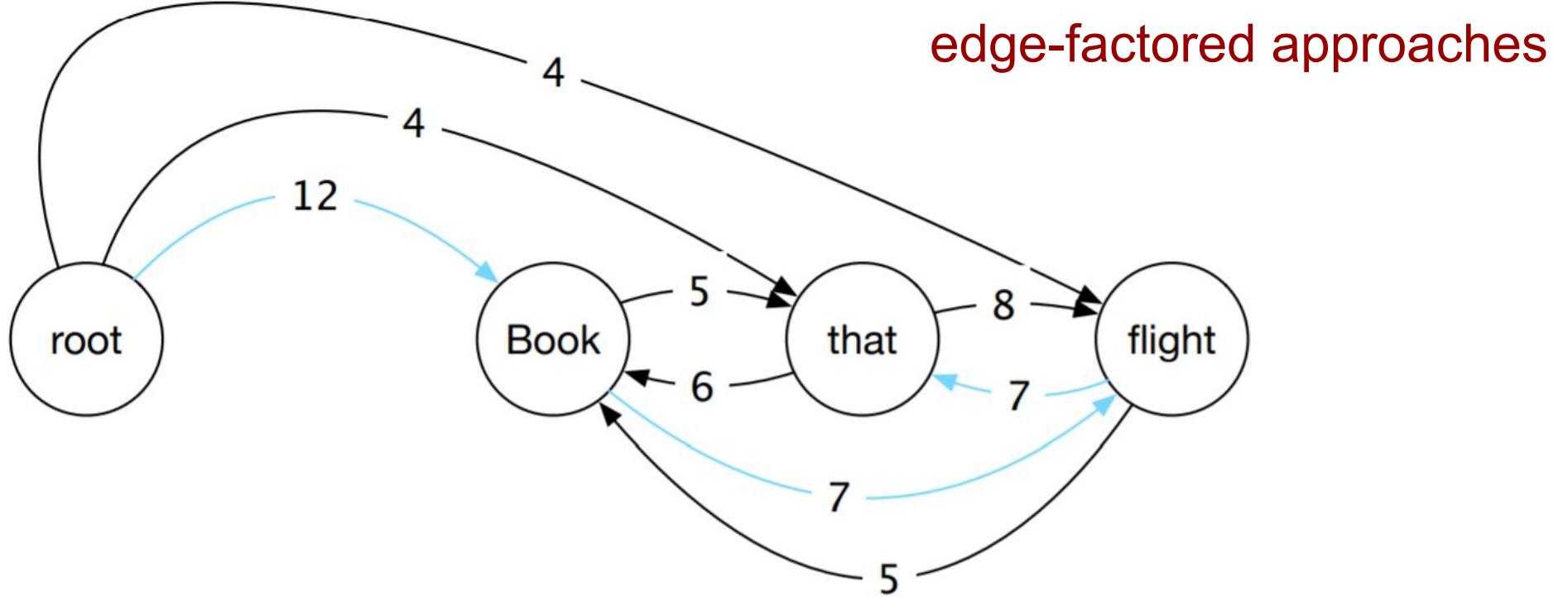
# Parsing algorithms

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- Transition based
  - greedy choice of local transitions guided by a good classifier
  - deterministic
  - MaltParser (Nivre et al. 2008), Stack LSTM (Dyer et al. 2015)
- Graph based
  - Minimum Spanning Tree for a sentence
  - non-projective
  - globally optimized
  - McDonald et al.'s (2005) MSTParser
  - Martins et al.'s (2009) Turbo Parser



# Graph-Based Parsing Algorithms



- Start with a fully-connected directed graph
- Find a Minimum Spanning Tree
  - Chu and Liu (1965) and Edmonds (1967) algorithm



# Chu-Liu Edmonds algorithm

```
function MAXSPANNINGTREE( $G=(V,E)$ ,  $\text{root}$ ,  $\text{score}$ ) returns spanning tree
```

```
 $F \leftarrow []$ 
 $T' \leftarrow []$ 
 $\text{score}' \leftarrow []$ 
for each  $v \in V$  do
     $\text{bestInEdge} \leftarrow \text{argmax}_{e=(u,v) \in E} \text{score}[e]$ 
    } Select best incoming edge for each node
     $F \leftarrow F \cup \text{bestInEdge}$ 
    for each  $e=(u,v) \in E$  do
         $\text{score}'[e] \leftarrow \text{score}[e] - \text{score}[\text{bestInEdge}]$ 
    } Subtract its score from all incoming edges
    if  $T=(V,F)$  is a spanning tree then return it
    else
         $C \leftarrow$  a cycle in  $F$ 
         $G' \leftarrow \text{CONTRACT}(G, C)$ 
         $T' \leftarrow \text{MAXSPANNINGTREE}(G', \text{root}, \text{score}')$ 
         $T \leftarrow \text{EXPAND}(T', C)$ 
    } Contract nodes if there are cycles
    return  $T$ 
} Stopping condition
} Recursively compute MST
} Expand contracted nodes
```

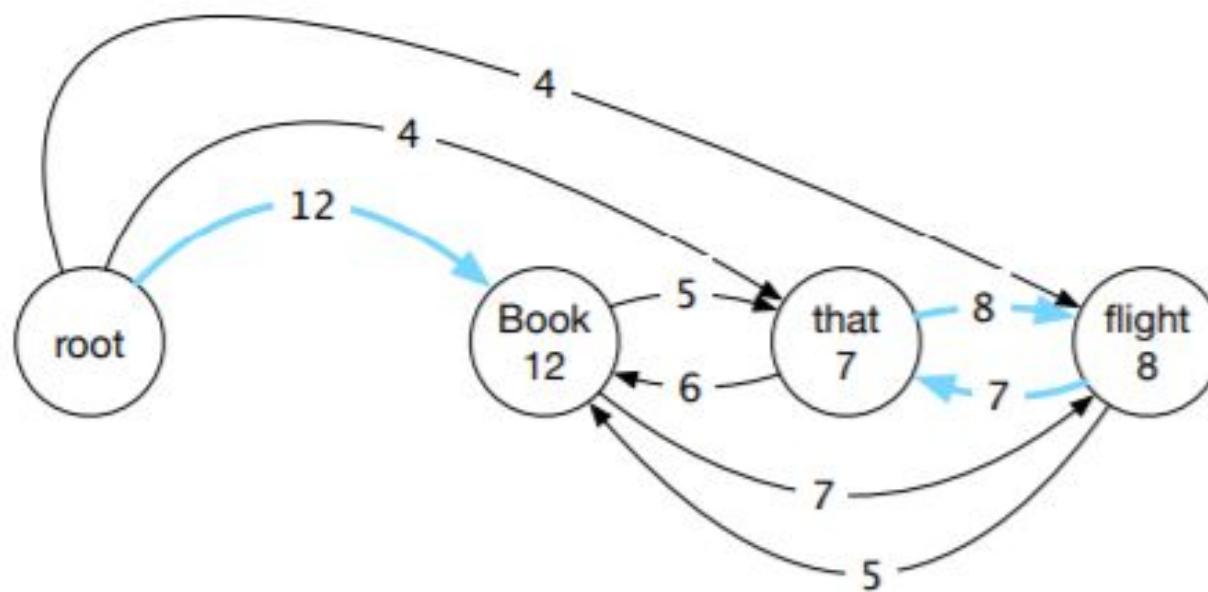
```
function CONTRACT( $G, C$ ) returns contracted graph
```

```
function EXPAND( $T, C$ ) returns expanded graph
```



# Chu-Liu Edmonds algorithm

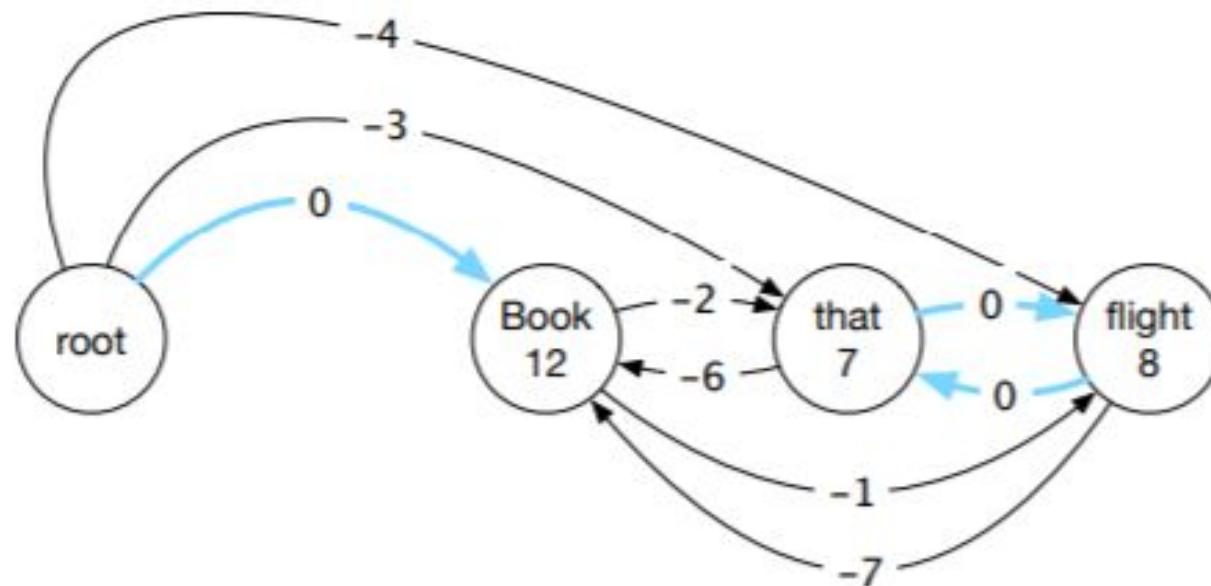
- Select best incoming edge for each node





# Chu-Liu Edmonds algorithm

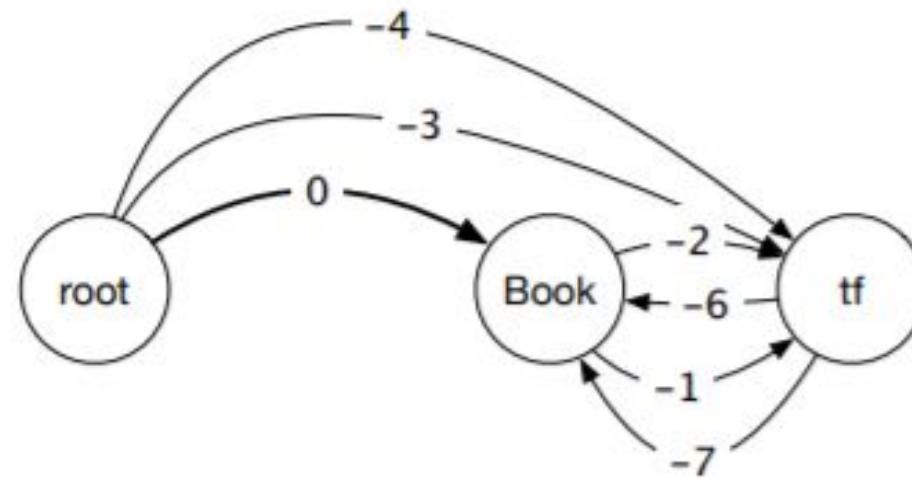
- Subtract its score from all incoming edges





# Chu-Liu Edmonds algorithm

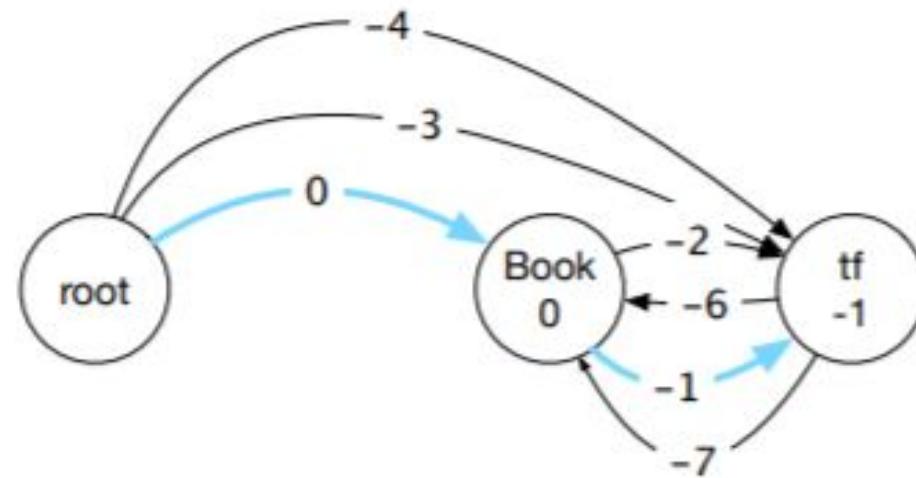
- Contract nodes if there are cycles





# Chu-Liu Edmonds algorithm

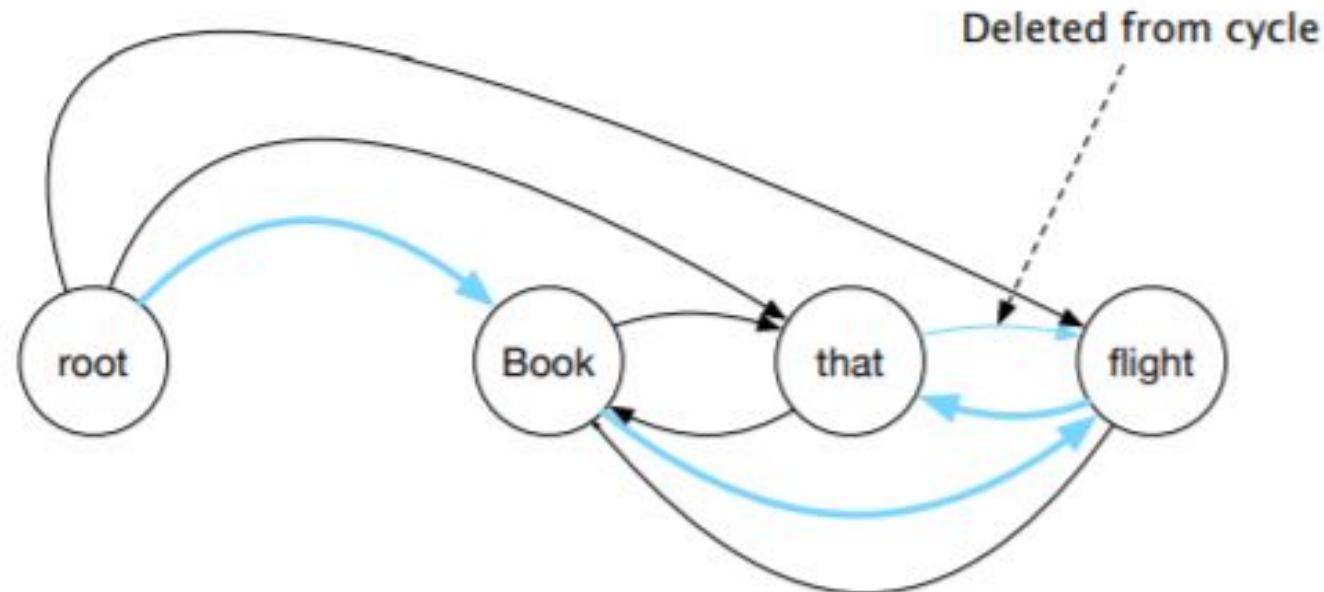
- Recursively compute MST





# Chu-Liu Edmonds algorithm

- Expand contracted nodes





# Scores

---

$$score(S, e) = w \cdot f$$

- Wordforms, lemmas, and parts of speech of the headword and its dependent.
- Corresponding features derived from the contexts before, after and between the words.
- Word embeddings.
- The dependency relation itself.
- The direction of the relation (to the right or left).
- The distance from the head to the dependent.



# Summary

---

- Transition-based
  - + Fast
  - + Rich features of context
  - - Greedy decoding
- Graph-based
  - + Exact or close to exact decoding
  - - Weaker features

Well-engineered versions of the approaches achieve comparable accuracy (on English), but make different errors  
→ combining the strategies results in a substantial boost in performance