Natural Language Processing

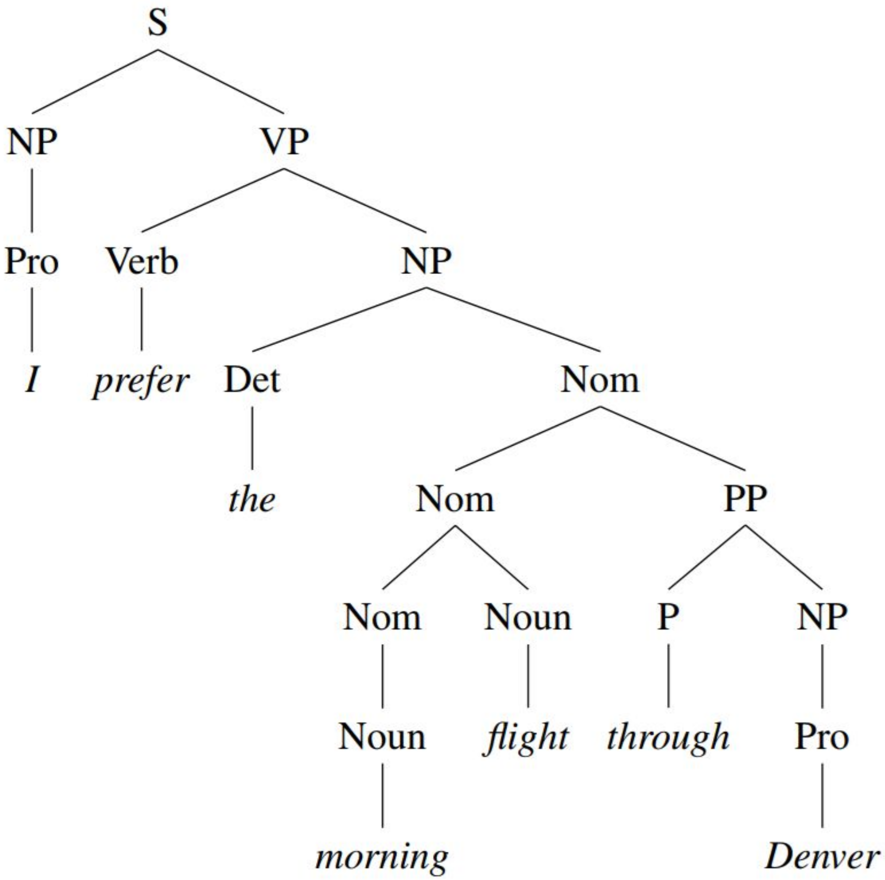
Syntactic parsing

Yulia Tsvetkov

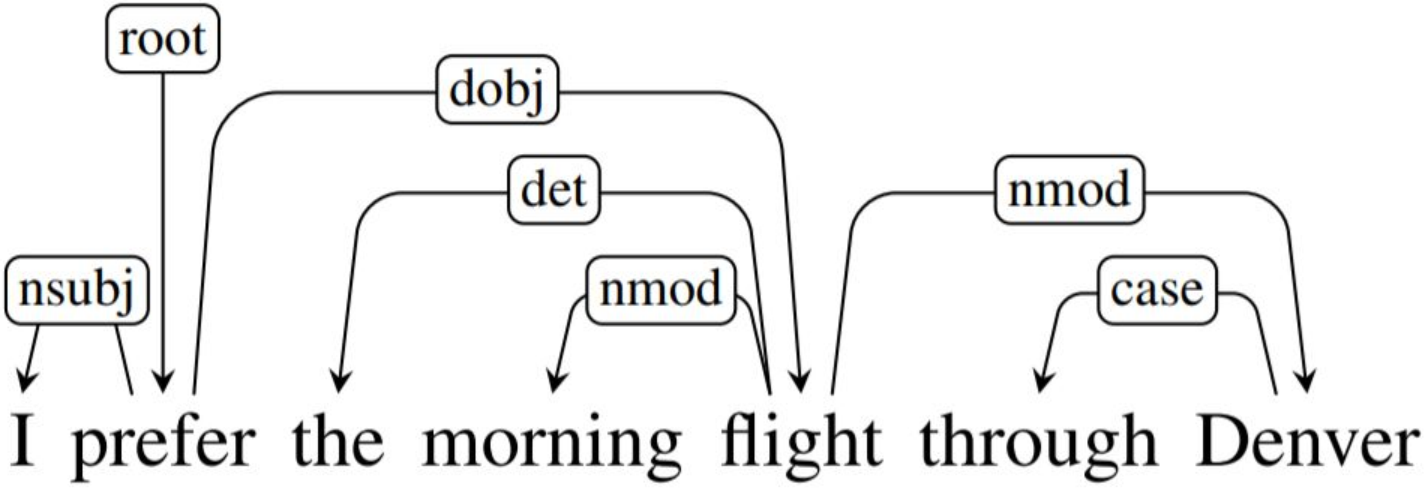
yuliats@cs.washington.edu

PAUL G. ALLEN SCHOOL OF COMPUTER SCIENCE & ENGINEERING

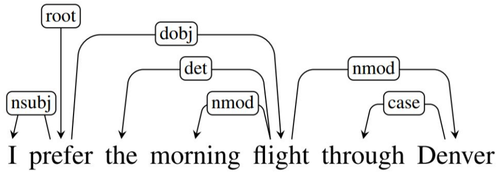
Constituent (phrase-structure) representation



Dependency representation



Dependency representation



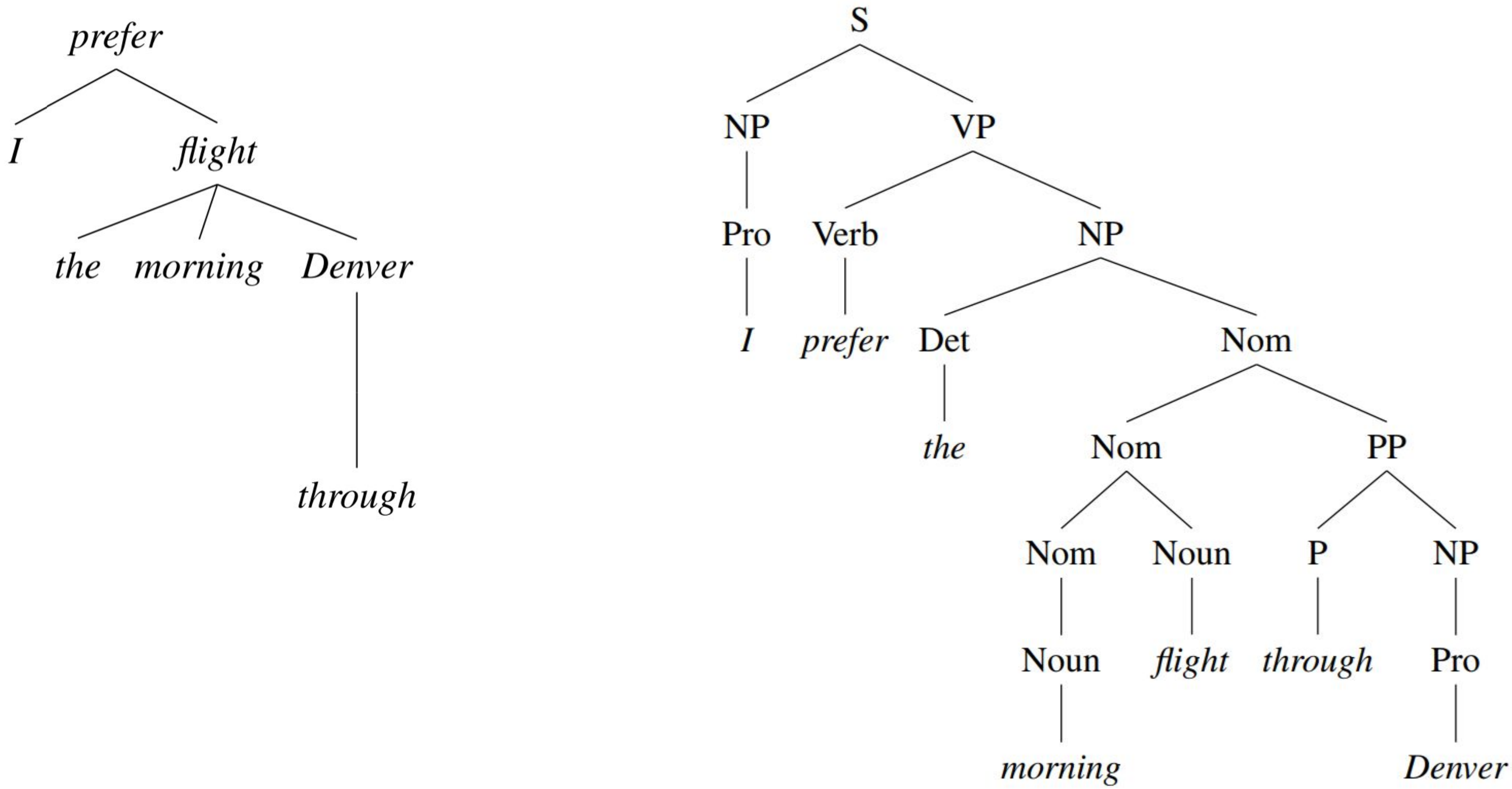
- A dependency structure can be defined as a directed graph G, consisting of
  - a set V of nodes – vertices, *words, punctuation, morphemes*
  - a set A of arcs – directed edges,
  - a linear precedence order < on V (word order).
- Labeled graphs
  - nodes in V are labeled with word forms (and annotation).
  - arcs in A are labeled with dependency types
  - $L = \{l_1, \ldots, l_{|L|}\}$ 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

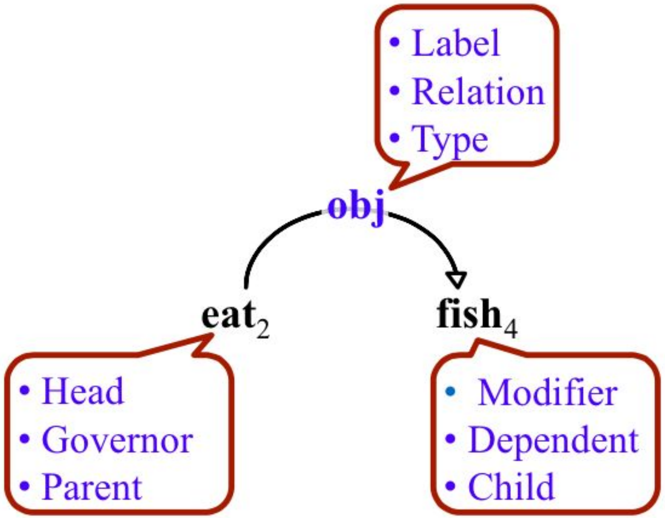
Перелет утренний я предпочитаю через Денвер

Через Денвер я предпочитаю утренний перелет

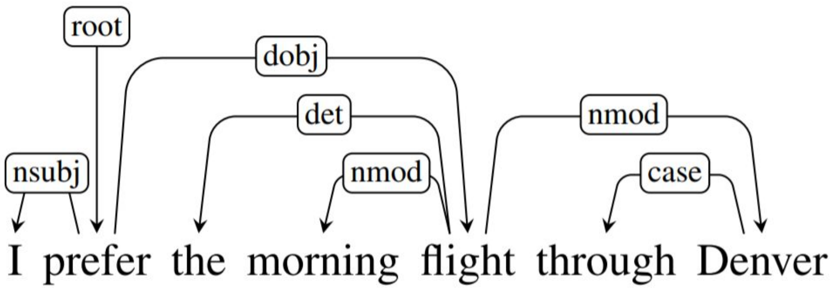
Я через Денвер предпочитаю утренний перелет

...

Dependency relations



Types of relationships



- The clausal relations NSUBJ and DOBJ identify the arguments: the subject and direct object of the predicate *cancel*

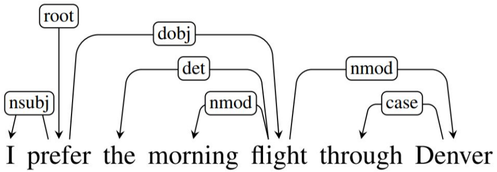
- The NMOD, DET, and CASE relations denote modifiers of the nouns *flights* and *Houston*.

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 Marneffe et al., 2014)

Dependency Constraints

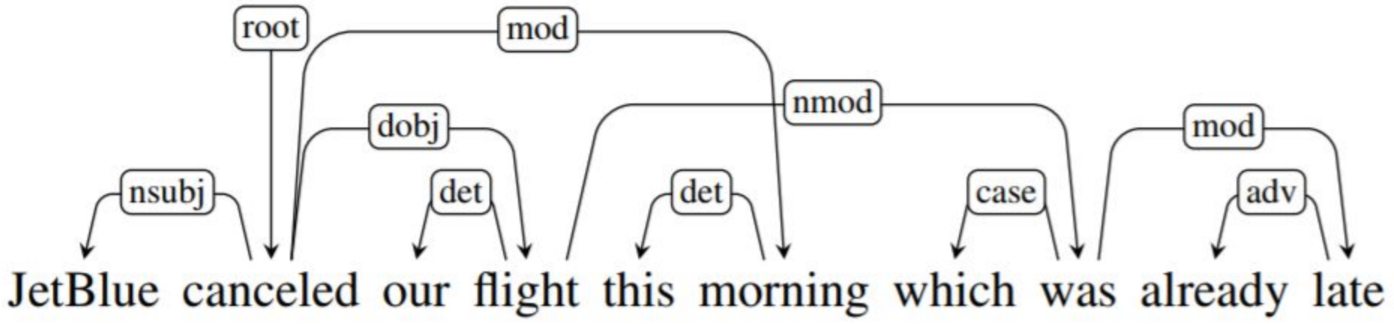


- Syntactic structure is complete (connectedness)
  - connectedness can be enforced by adding a special root node
- Syntactic structure is hierarchical (acyclicity)
  - there is a unique pass from the root to each vertex
- Every word has at most one syntactic head (single-head constraint)
  - except 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%)

Percentage of non-projective trees for some treebanks of the CoNLL-X Shared Task and English.

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/
  - 150 treebanks, 90 languages

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

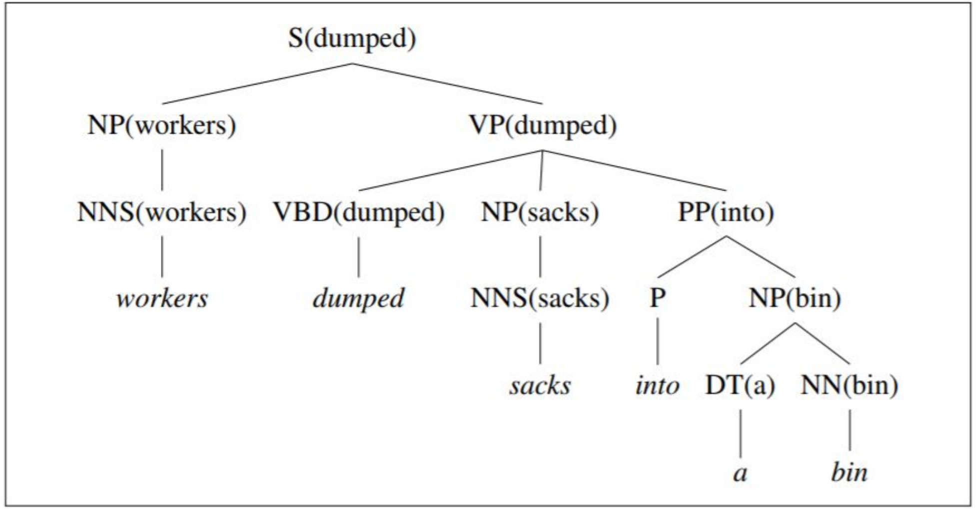


Figure 10.11 A lexicalized tree from Collins (1999).

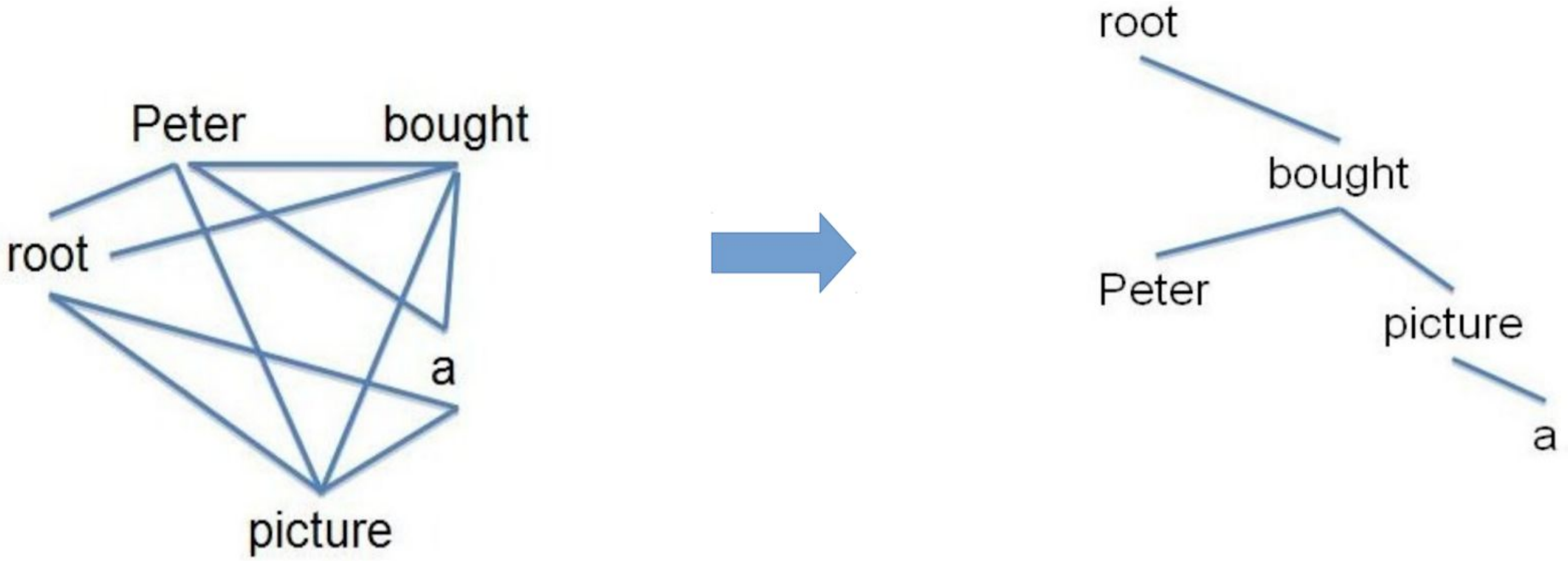
Parsing problem

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

This amounts to assigning a syntactic head $\boldsymbol{i}$ and a label $\boldsymbol{l}$ to every node $\boldsymbol{j}$ corresponding to a word $\boldsymbol{x_j}$ 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

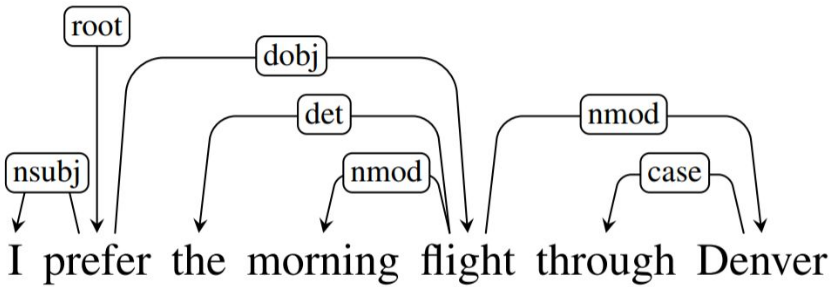


Parsing algorithms

- 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

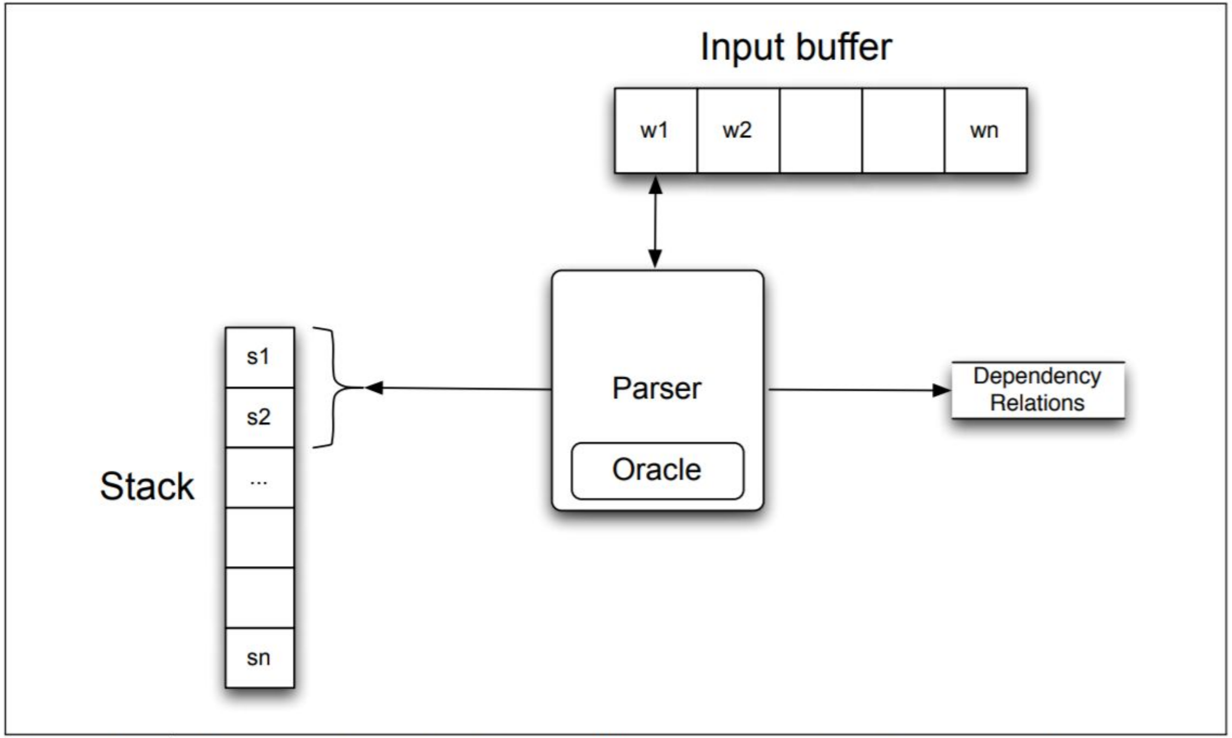


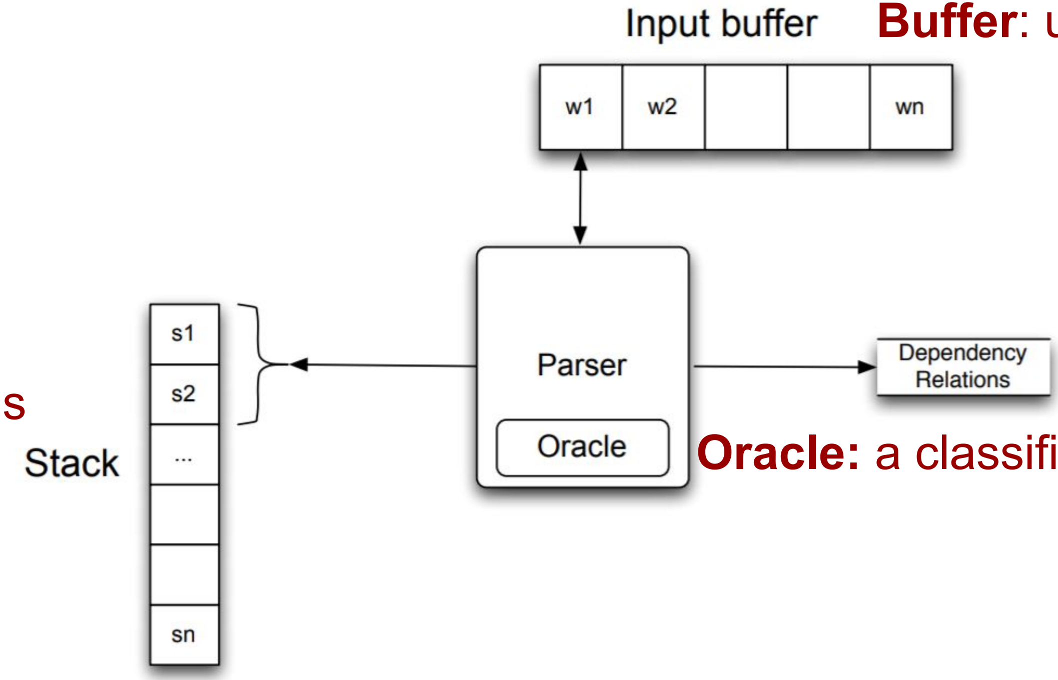
Figure 13.5 Basic transition-based parser. The parser examines the top two elements of the stack and selects an action based on consulting an oracle that examines the current configuration.

Configuration

Buffer: unprocessed words

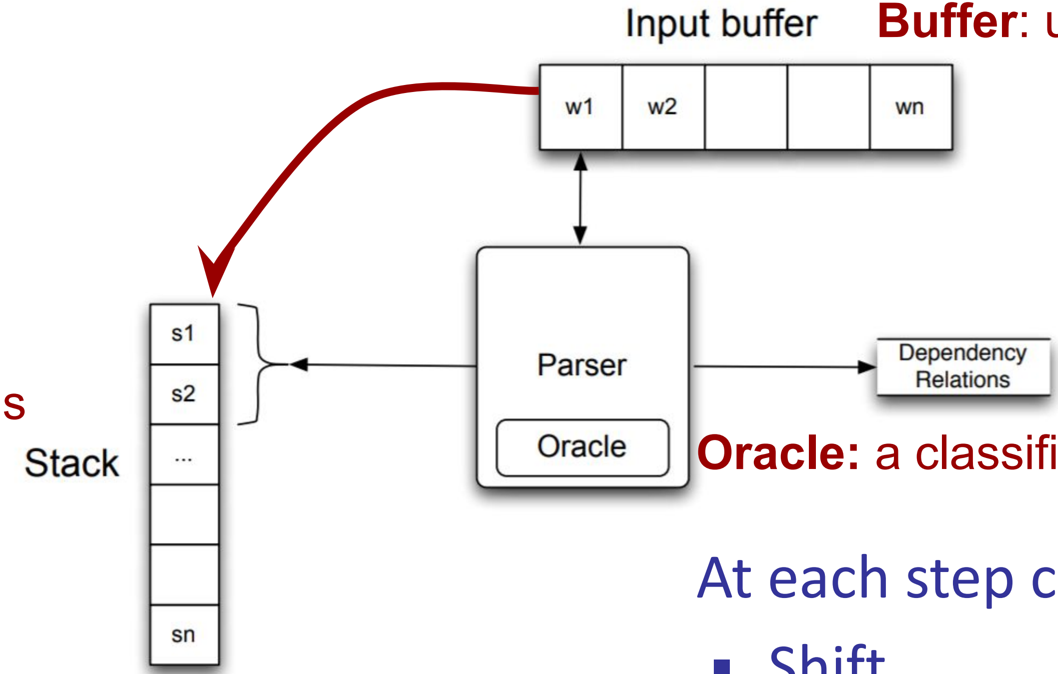
Stack: partially processed words

Oracle: a classifier



Operations

Buffer: unprocessed words



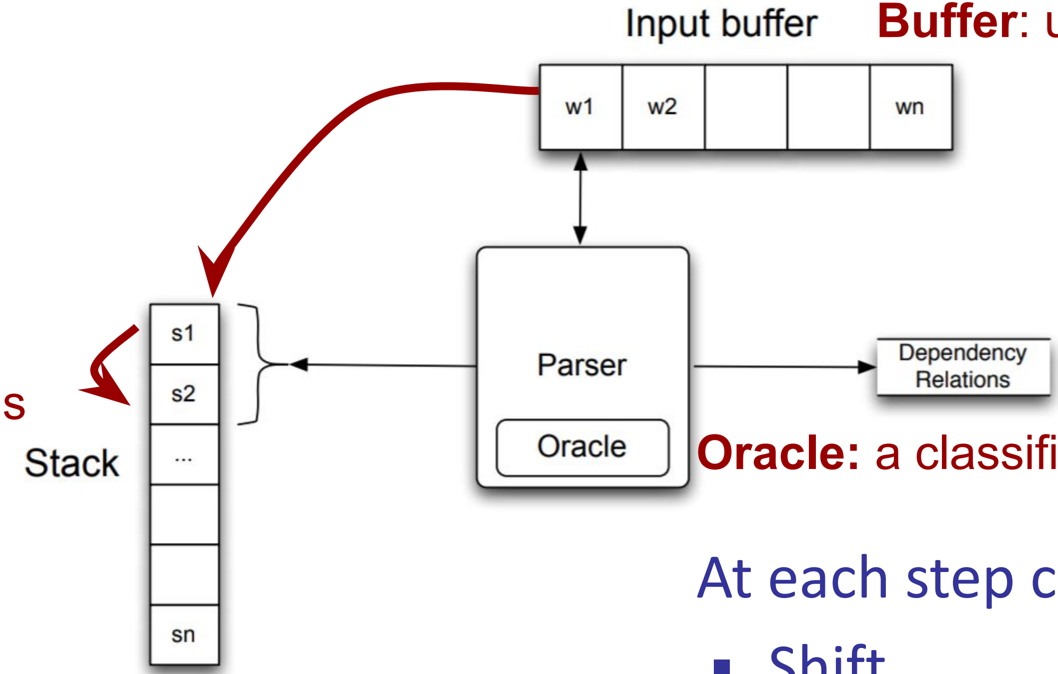
Stack: partially processed words

Oracle: a classifier

At each step choose:

- Shift

Operations



Buffer: unprocessed words

Stack: partially processed words

Oracle: a classifier

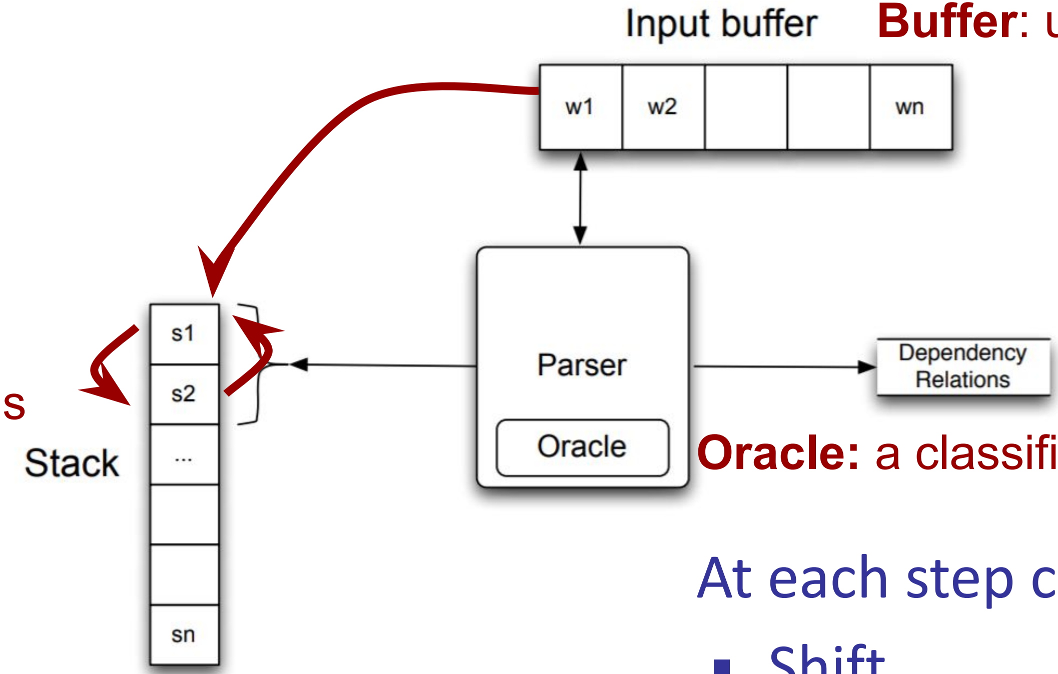
At each step choose:

- Shift
- Reduce left

Operations

Buffer: unprocessed words

Stack: partially processed words



Oracle: a classifier

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:

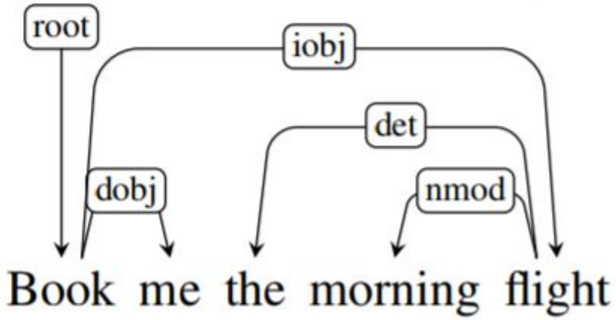
- Shift
  - remove w1 from the buffer, add it to the top of the stack as s1
- LeftArc or Reduce left
  - assert a head-dependent relation between s1 and s2
  - remove s2 from the stack
- RightArc or Reduce right
  - assert a head-dependent relation between s2 and s1
  - remove s1 from the stack

Shift-Reduce Parsing

Book me the morning flight

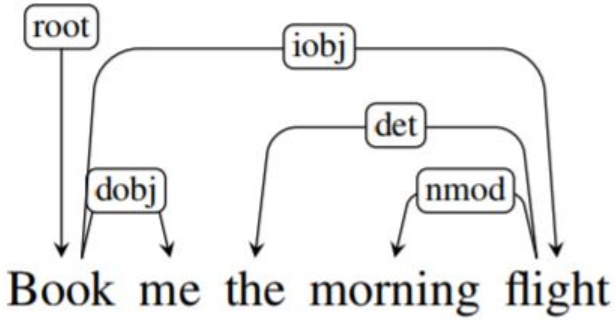
Step	Stack	Word List	Action	Relation Added

Shift-Reduce Parsing



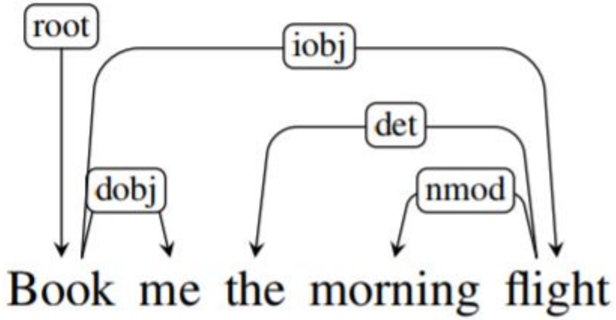
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]		

Shift-Reduce Parsing



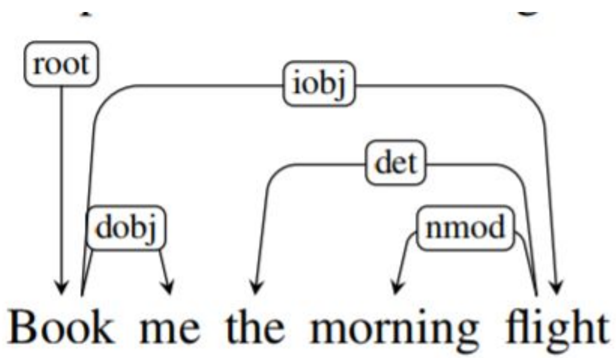
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]		

Shift-Reduce Parsing



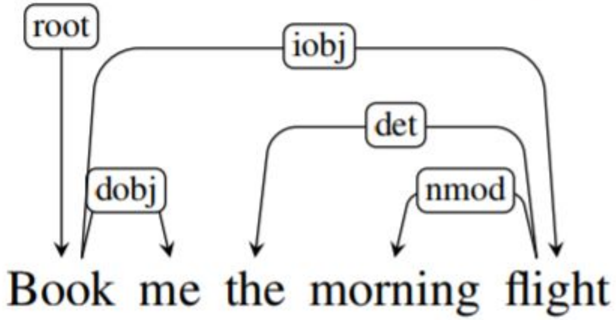
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]		

Shift-Reduce Parsing



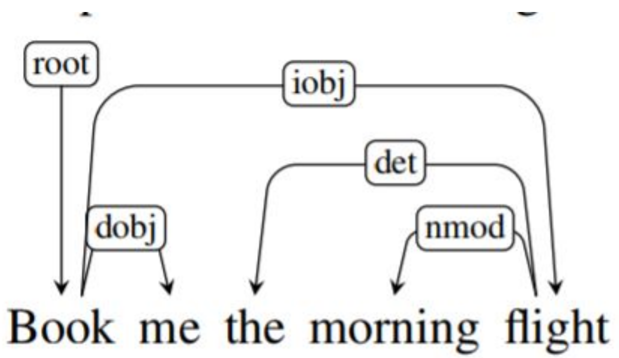
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	

Shift-Reduce Parsing



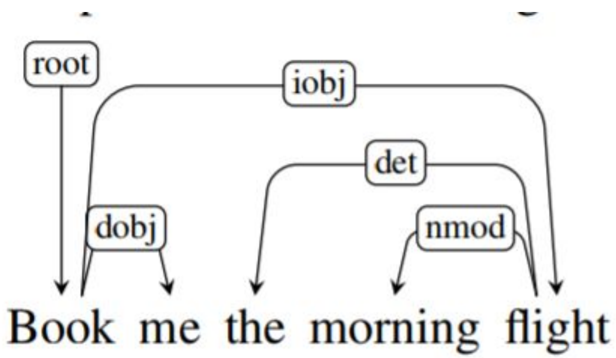
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]		

Shift-Reduce Parsing



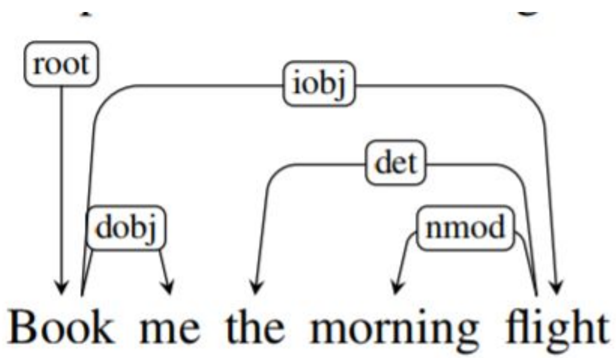
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	

Shift-Reduce Parsing



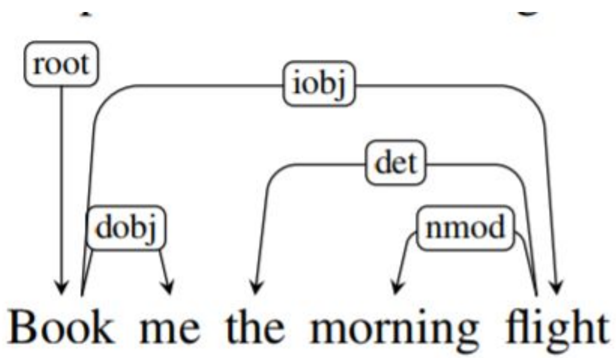
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)

Shift-Reduce Parsing



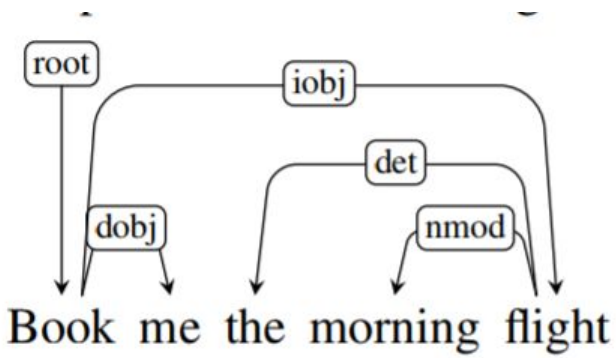
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]		

Shift-Reduce Parsing



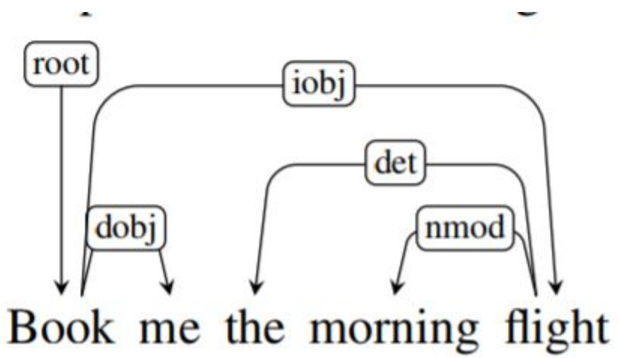
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book $\rightarrow$ me)
3	[root, book]	[the, morning, flight]	SHIFT	

Shift-Reduce Parsing



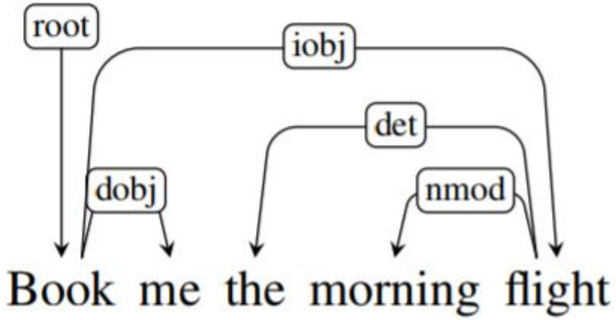
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book $\rightarrow$ me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]		

Shift-Reduce Parsing



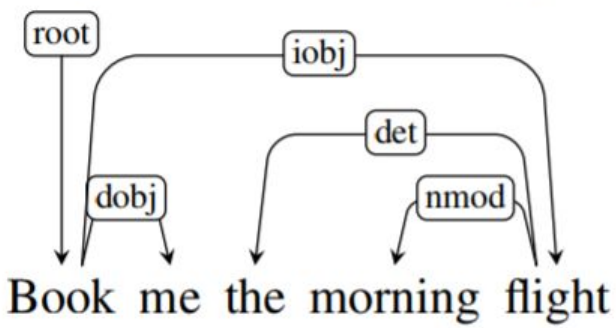
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book $\rightarrow$ me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	

Shift-Reduce Parsing



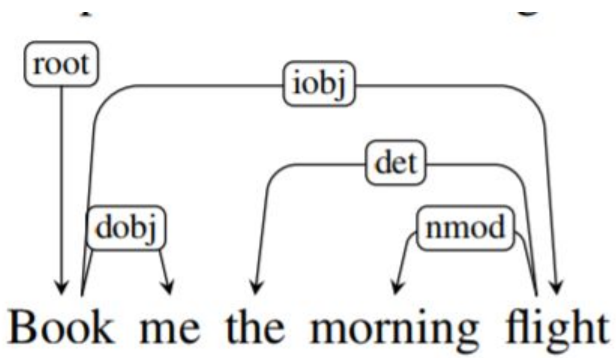
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root,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

Shift-Reduce Parsing



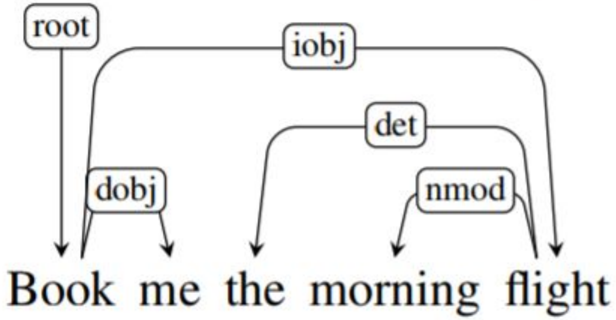
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book $\rightarrow$ me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT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

Shift-Reduce Parsing



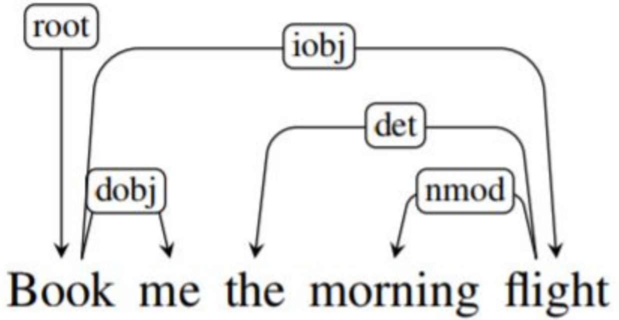
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root,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

Shift-Reduce Parsing



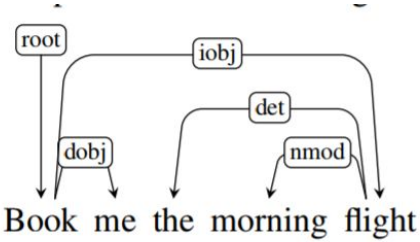
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book $\rightarrow$ me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT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

Shift-Reduce Parsing



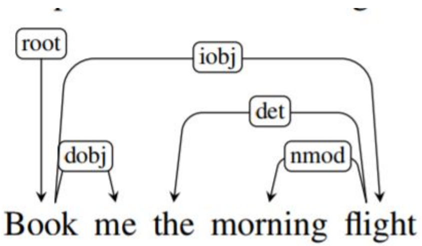
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book → me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT	
5	[root,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



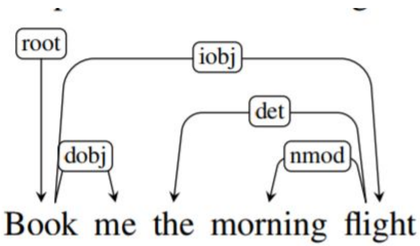
Step	Stack	Word List	Action	Relation Added
0	[root]	[book, me, the, morning, flight]	SHIFT	
1	[root, book]	[me, the, morning, flight]	SHIFT	
2	[root, book, me]	[the, morning, flight]	RIGHTARC	(book $\rightarrow$ me)
3	[root, book]	[the, morning, flight]	SHIFT	
4	[root, book, the]	[morning, flight]	SHIFT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

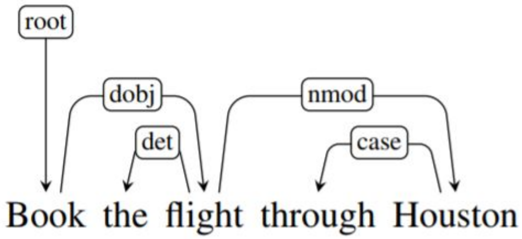
Oracle decisions can correspond to unlabeled or labeled arcs

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?

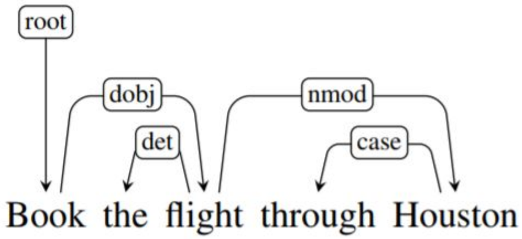
Training an Oracle

- 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
- morphological features for some languages
- previous relations
- conjunction features (e.g. Zhang&Clark'08; Huang&Sagae'10; Zhang&Nivre'11)

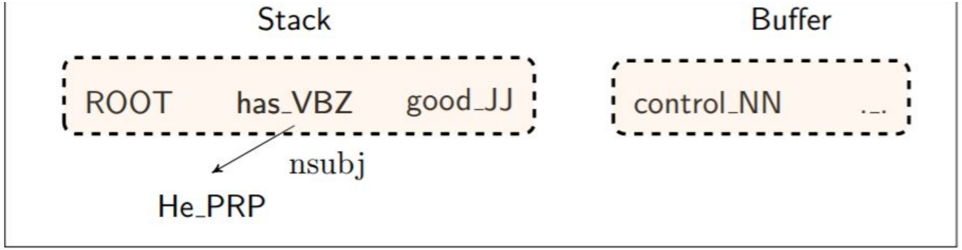
$$\langle s_1.w = \mathit{flights}, op = \mathit{shift}\rangle$$
$$\langle s_2.w = \mathit{canceled}, op = \mathit{shift}\rangle$$
$$\langle s_1.t = \mathit{NNS}, op = \mathit{shift}\rangle$$
$$\langle s_2.t = \mathit{VBD}, op = \mathit{shift}\rangle$$
$$\langle b_1.w = \mathit{to}, op = \mathit{shift}\rangle$$
$$\langle b_1.t = \mathit{TO}, op = \mathit{shift}\rangle$$
$$\langle s_1.wt = \mathit{flightsNNS}, op = \mathit{shift}\rangle$$
$$\langle s_1.t \circ s_2.t = \mathit{NNSVBD}, op = \mathit{shift}\rangle$$

Source	**Feature templates**		
One word	$s_1.w$	$s_1.t$	$s_1.wt$
	$s_2.w$	$s_2.t$	$s_2.wt$
	$b_1.w$	$b_1.w$	$b_0.wt$
Two word	$s_1.w \circ s_2.w$	$s_1.t \circ s_2.t$	$s_1.t \circ b_1.w$
	$s_1.t \circ s_2.wt$	$s_1.w \circ s_2.w \circ s_2.t$	$s_1.w \circ s_1.t \circ s_2.t$
	$s_1.w \circ s_1.t \circ s_2.t$	$s_1.w \circ s_1.t$	

Learning

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

Chen & Manning 2014



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

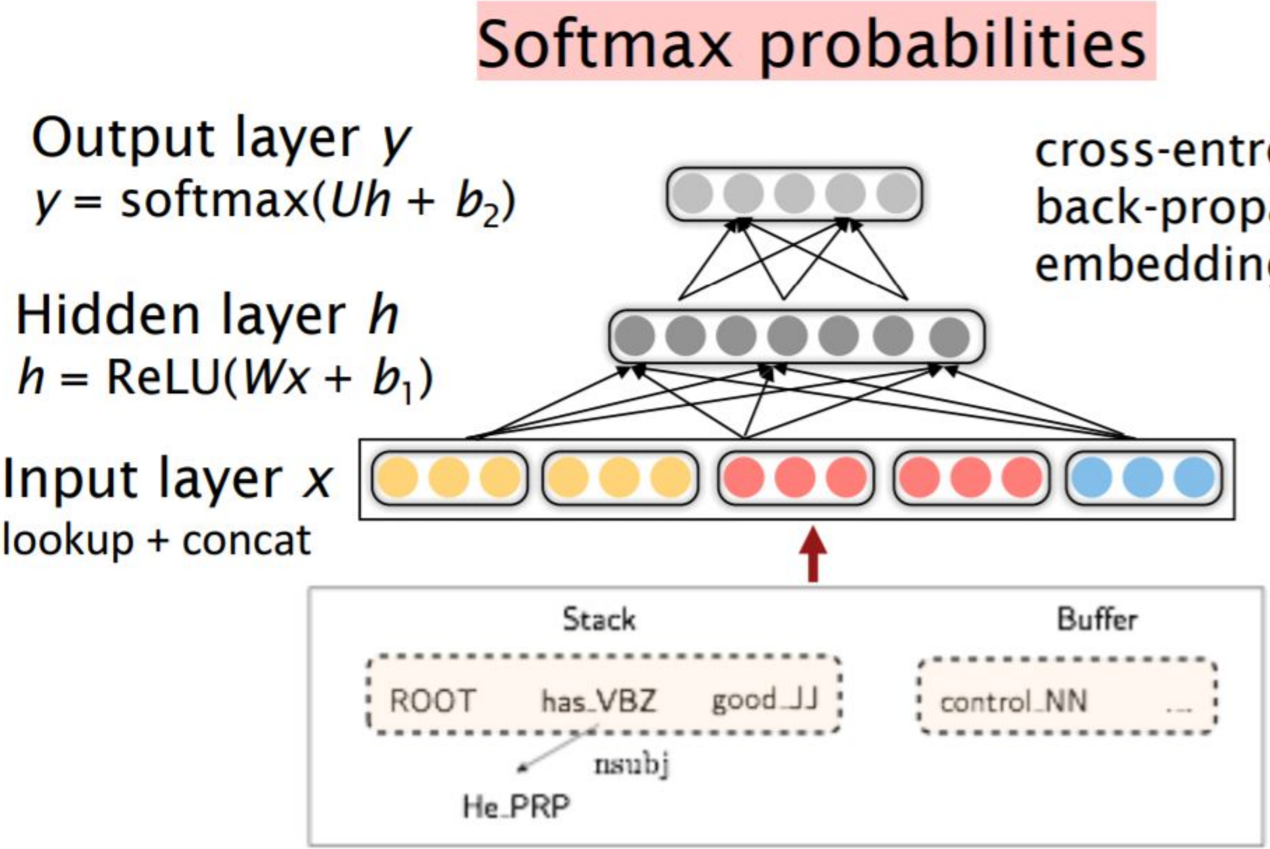
0	0	0	1	0	0	1	0	...	0	0	1	0

Indicator features

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

Slides by Danqi Chen & Chris Manning

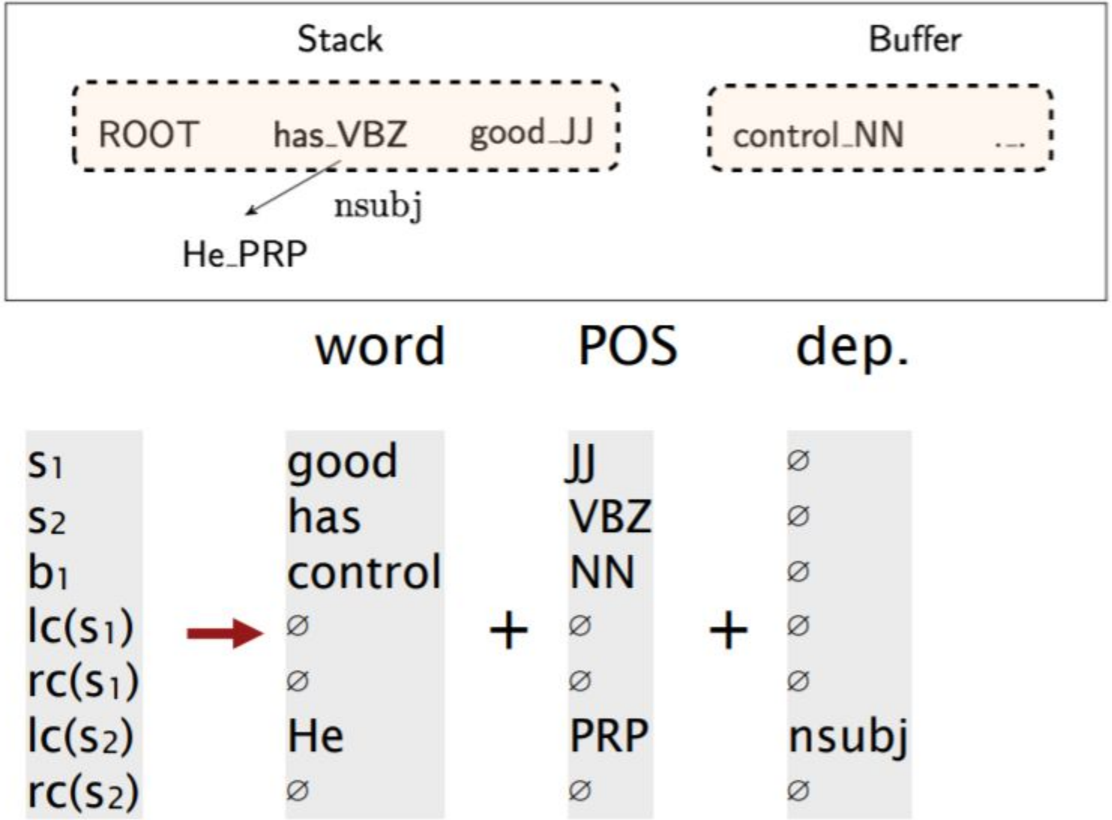
Chen & Manning 2014



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

Chen & Manning 2014

- Features
  - s1, s2, s3, b1, b2, b3
  - leftmost/rightmost children of s1 and s2
  - leftmost/rightmost grandchildren of s1 and s2
  - POS tags for the above
  - arc labels for children/grandchildren



Evaluation of Dependency Parsers

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

- 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	**92.3***	89.6*	8
C & M 2014	92.0	**89.7**	**654**

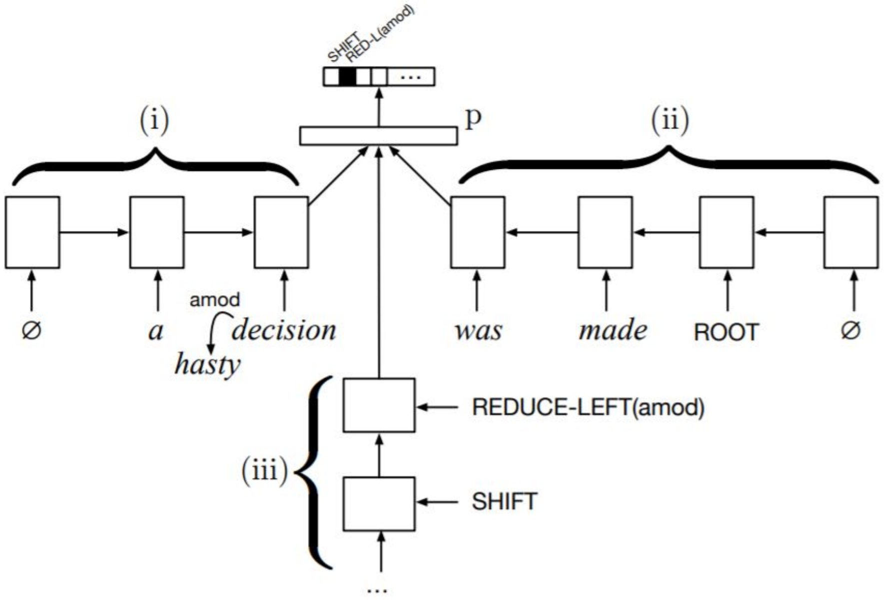
Follow-up

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

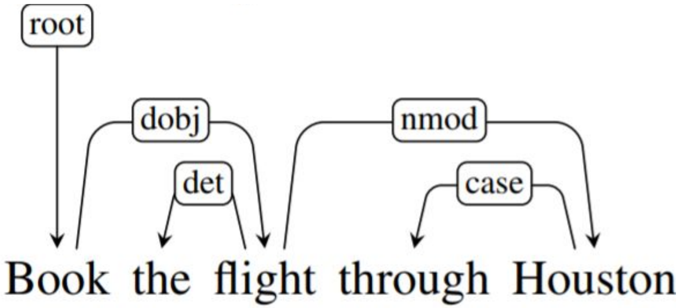
Stack LSTMs (Dyer et al. 2015)

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

Chris Dyer[♣♠] **Miguel Ballesteros**[♢♠] **Wang Ling**[♠] **Austin Matthews**[♠] **Noah A. Smith**[♠]
[♣]Marianas Labs [♢]NLP Group, Pompeu Fabra University [♠]Carnegie Mellon University
chris@marianaslabs.com, miguel.ballesteros@upf.edu,



Arc-Eager



- LEFTARC: Assert a head-dependent relation between s1 and b1; pop the stack.
- RIGHTARC: Assert a head-dependent relation between s1 and b1; shift b1 to be s1.
- SHIFT: Remove b1 and push it to be s1.
- 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

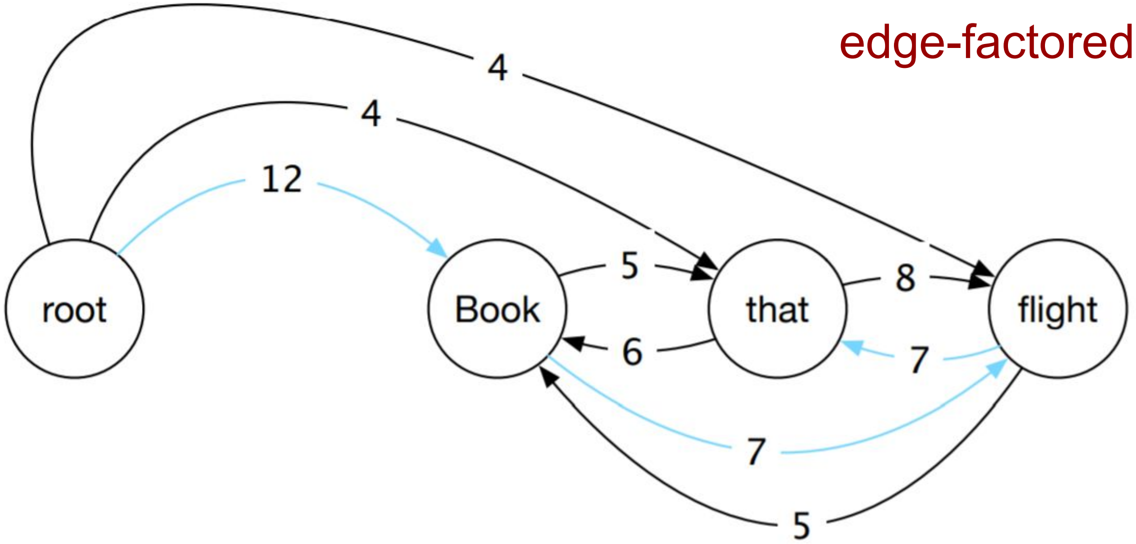
```
function DEPENDENCYBEAMPARSE(words, width) returns dependency tree

  state ← {[root], [words], [], 0.0}     ;initial configuration
  agenda ← ⟨state⟩;       initial agenda

  while agenda contains non-final states
    newagenda ← ⟨⟩
    for each state ∈ agenda do
      for all {t | t ∈ VALIDOPERATORS(state)} do
        child ← APPLY(t, state)
        newagenda ← ADDTOBEAM(child, newagenda, width)
    agenda ← newagenda
  return BESTOF(agenda)

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

  if LENGTH(agenda) < width then
     agenda ← INSERT(state, agenda)
  else if SCORE(state) > SCORE(WORSTOF(agenda))
     agenda ← REMOVE(WORSTOF(agenda))
     agenda ← INSERT(state, agenda)
  return agenda
```

Parsing algorithms

- 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

edge-factored approaches



- 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), root, score) returns spanning tree

    F ← []
    T' ← []
    score' ← []
    for each v ∈ V do
       bestInEdge ← argmax_{e=(u,v)∈ E} score[e]
       F ← F ∪ bestInEdge
       for each e=(u,v) ∈ E do
          score'[e] ← score[e] − score[bestInEdge]

       if T=(V,F) is a spanning tree then return it
       else
          C ← a cycle in F
          G' ← Contract(G, C)
          T' ← MaxSpanningTree(G', root, score')
          T ← Expand(T', C)
          return T

function Contract(G, C) returns contracted graph

function Expand(T, C) returns expanded graph
```

Select best incoming edge for each node

Subtract its score from all incoming edges

Stopping condition

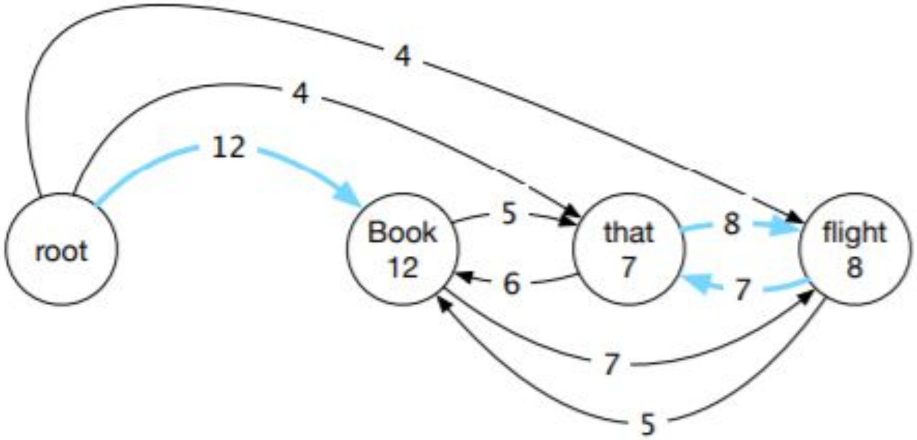
Contract nodes if there are cycles

Recursively compute MST

Expand contracted nodes

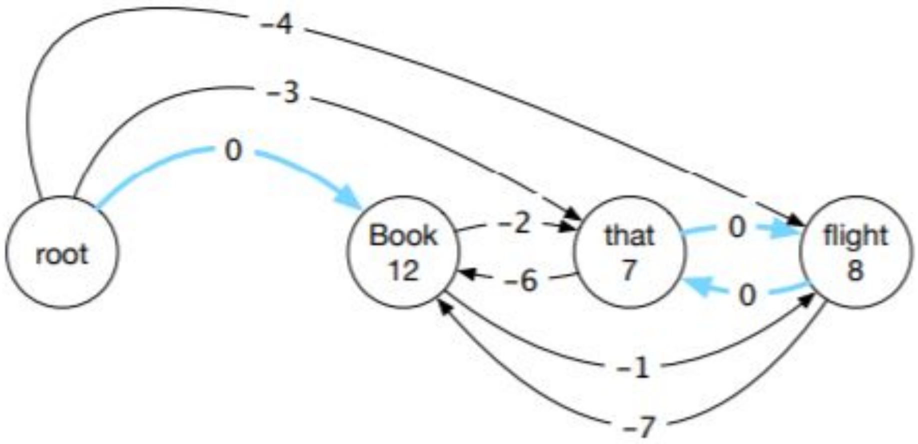
Chu-Liu Edmonds algorithm

- Select best incoming edge for each node



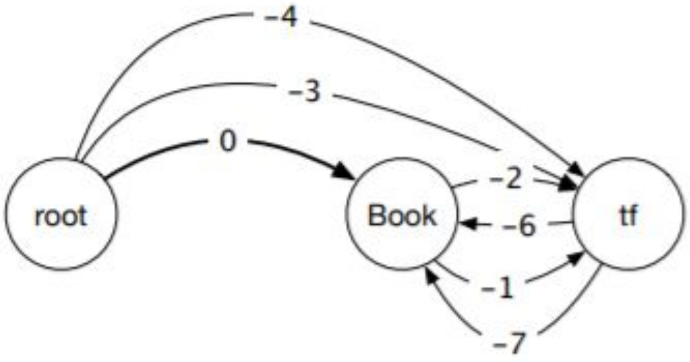
Chu-Liu Edmonds algorithm

- Subtract its score from all incoming edges



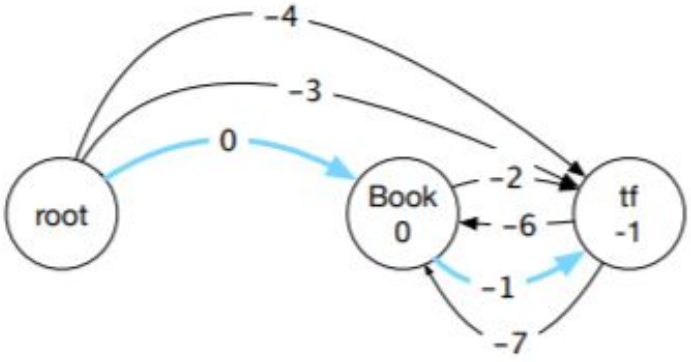
Chu-Liu Edmonds algorithm

- Contract nodes if there are cycles



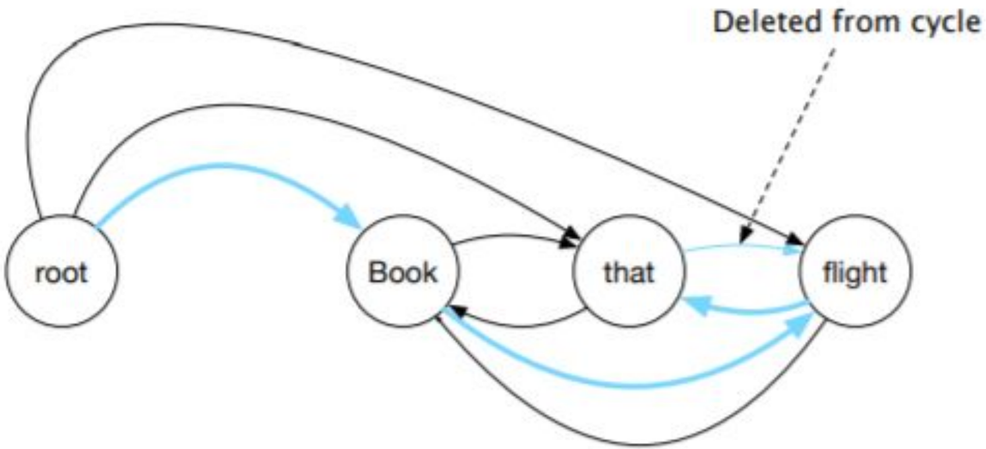
Chu-Liu Edmonds algorithm

- 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