Training Deterministic Parsers Using Non-Deterministic Oracles

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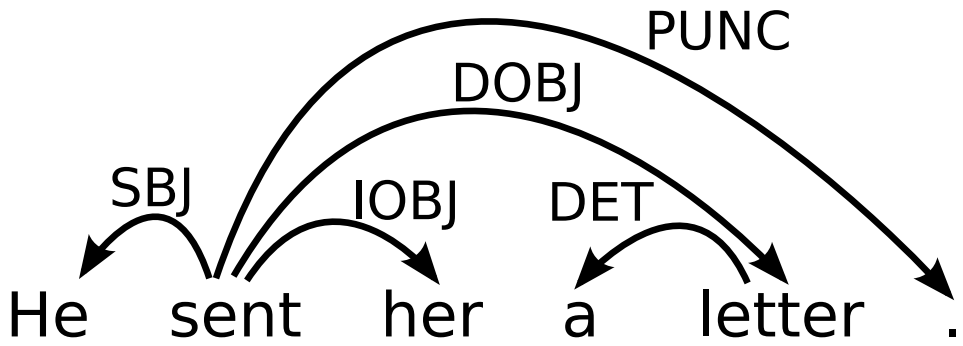
Introduction



- Deterministic dependency parsing:
  - Very fast: 10^5 words per second
  - Fairly accurate: 2–3% below the state of the art
- How can we improve accuracy without losing speed?

Introduction

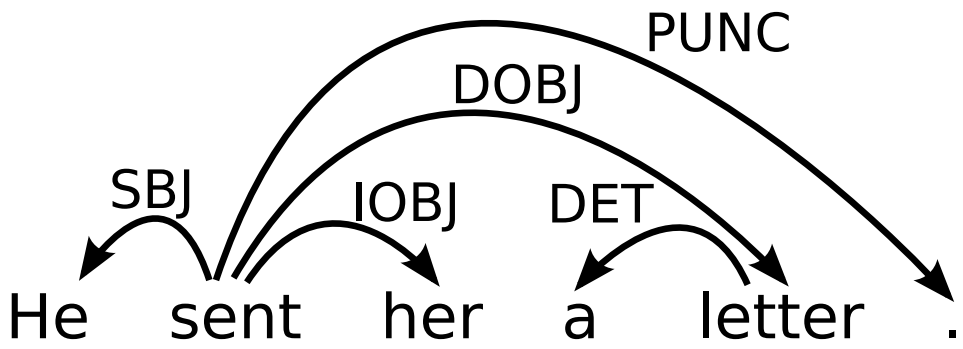
- Transition-based dependency parsing:
  - Define a transition system for dependency parsing
  - Train a classifier for predicting the next transition
  - Use the classifier to do deterministic parsing
- Current practice:
  - Train classifier on derivations produced by an oracle
  - Leads to error propagation at parsing time
  - Can be mitigated by using beam search – slowdown
- Novel idea:
  - Explore a larger search space during training
  - Allow the parser to make mistakes and recover
  - Requires a new type of oracle

Outline

1. Transition-based dependency parsing
2. Old oracles – and why they are a problem
3. New oracles – and why they should help
4. Experiments

Dependency Trees

- A dependency tree is a labeled directed tree T with
  - a set V of nodes, labeled with words
  - a set A of arcs, labeled with dependency types
- Notation:
  - Arc (w_i, d, w_j) links head w_i to dependent w_j with label d
  - Shorthand: $w_i \xrightarrow{d} w_j \Leftrightarrow (w_i, d, w_j) \in A$



Transition System: Configurations

- A parser configuration is a triple $c = (S, B, A)$, where
  - S = a stack $[\ldots, w_i]_S$ of partially processed words,
  - B = a buffer $[w_j, \ldots]_B$ of remaining input word,
  - A = a set of labeled arcs (w_i, d, w_j).
- Initialization:

  $([\,]_S, [w_1, \ldots, w_n]_B, \{\,\})$
- Termination:

  $(S, [\,]_B, A)$

Transition System: Transitions

$$\text{Left-Arc}(d)\ \frac{([\ldots, w_i]_S,\ [w_j, \ldots]_B,\ A)}{([\ldots]_S,\ [w_j, \ldots]_B,\ A \cup \{(w_j, d, w_i)\})}\ \neg\text{HEAD}(w_i)$$

$$\text{Right-Arc}(d)\ \frac{([\ldots, w_i]_S,\ [w_j, \ldots]_B,\ A)}{([\ldots, w_i, w_j]_S,\ [\ldots]_B,\ A \cup \{(w_i, d, w_j)\})}$$

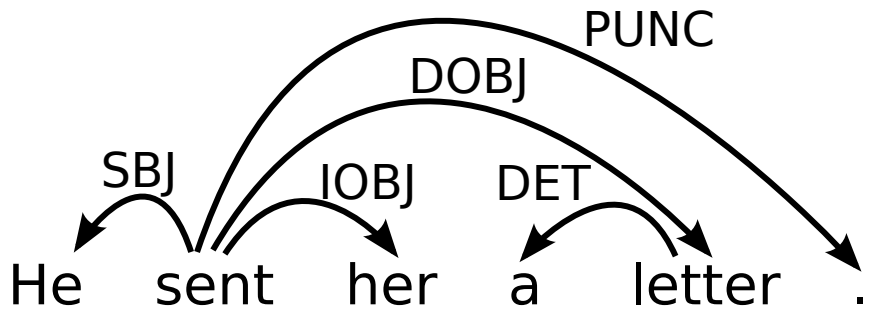
$$\text{Reduce}\ \frac{([\ldots, w_i]_S,\ B,\ A)}{([\ldots]_S,\ B,\ A)}\ \text{HEAD}(w_i)$$

$$\text{Shift}\ \frac{([\ldots]_S,\ [w_i, \ldots]_B,\ A)}{([\ldots, w_i]_S,\ [\ldots]_B,\ A)}$$

Parse Example

Transitions:

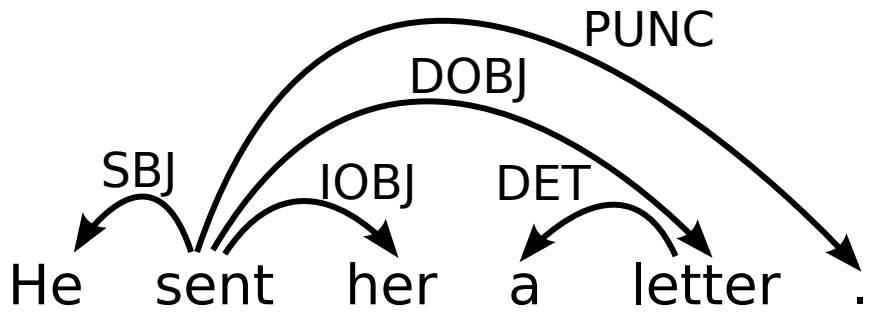
Stack	**Buffer**	**Arcs**
$[\,]_S$	[He, sent, her, a, letter, .]$_B$	



Parse Example

Transitions: SH

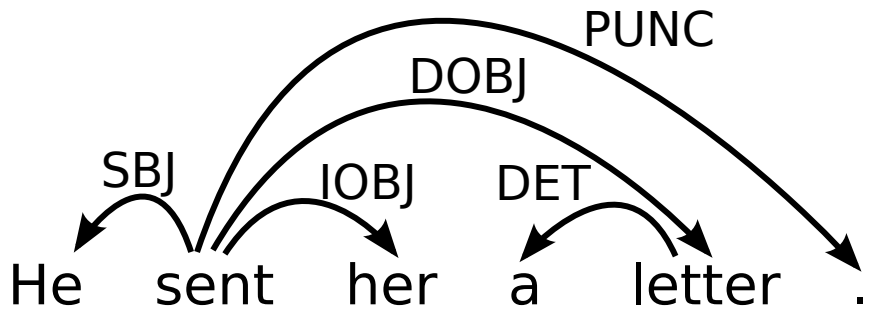
Stack	**Buffer**	**Arcs**
$[\text{He}]_S$	$[\text{sent, her, a, letter, .}]_B$	



Parse Example

Transitions: SH-LA

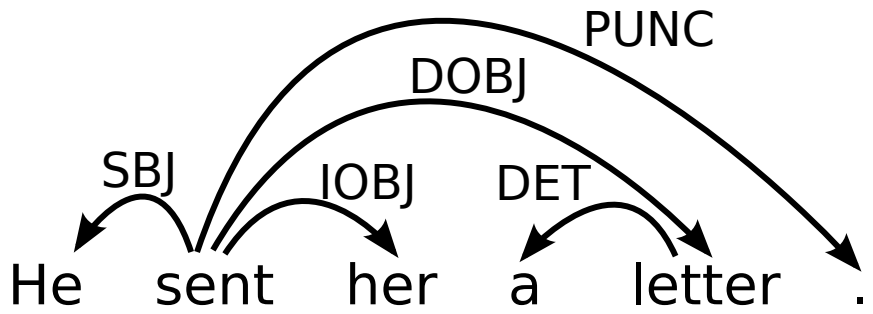
Stack	**Buffer**	**Arcs**
$[\,]_S$	$[\text{sent, her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\longleftarrow}$ sent



Parse Example

Transitions: SH-LA-SH

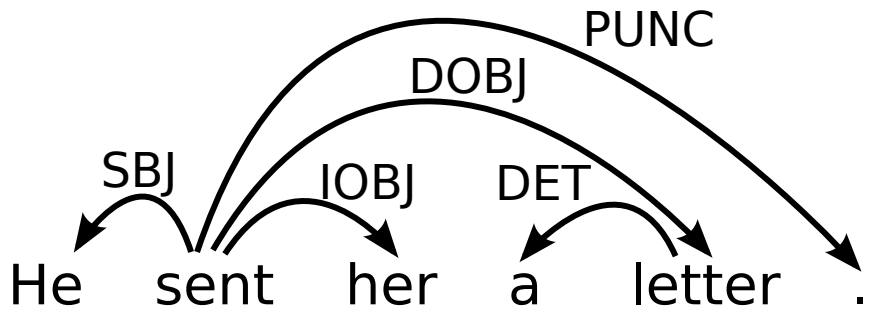
Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[\text{her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\longleftarrow}$ sent



Parse Example

Transitions: SH-LA-SH-RA

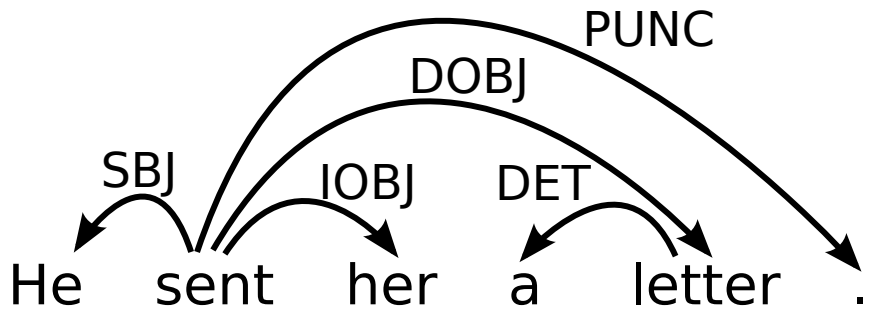
Stack	**Buffer**	**Arcs**
$[\text{sent, her}]_S$	$[\text{a, letter, .}]_B$	He $\overset{\text{SBJ}}{\longleftarrow}$ sent
		sent $\overset{\text{IOBJ}}{\longrightarrow}$ her



Parse Example

Transitions: SH-LA-SH-RA-SH

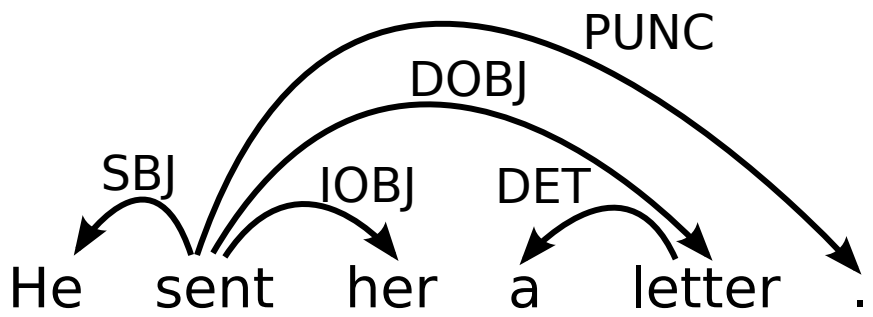
Stack	**Buffer**	**Arcs**
$[\text{sent, her, a}]_S$	$[\text{letter, .}]_B$	He $\overset{\text{SBJ}}{\longleftarrow}$ sent
		sent $\overset{\text{IOBJ}}{\longrightarrow}$ her



Parse Example

Transitions: SH-LA-SH-RA-SH-LA

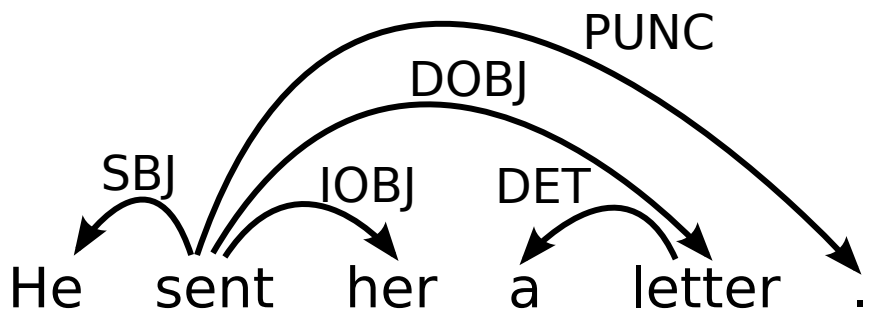
Stack	**Buffer**	**Arcs**
$[\text{sent, her}]_S$	$[\text{letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent
		sent $\overset{\text{IOBJ}}{\rightarrow}$ her
		a $\overset{\text{DET}}{\leftarrow}$ letter



Parse Example

Transitions: SH-LA-SH-RA-SH-LA-RE

Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[\text{letter}, .]_B$	He $\overset{\text{SBJ}}{\longleftarrow}$ sent
		sent $\overset{\text{IOBJ}}{\longrightarrow}$ her
		a $\overset{\text{DET}}{\longleftarrow}$ letter



Parse Example

Transitions: SH-LA-SH-RA-SH-LA-RE-RA

Stack	**Buffer**
$[\text{sent, letter}]_S$	$[.]_B$

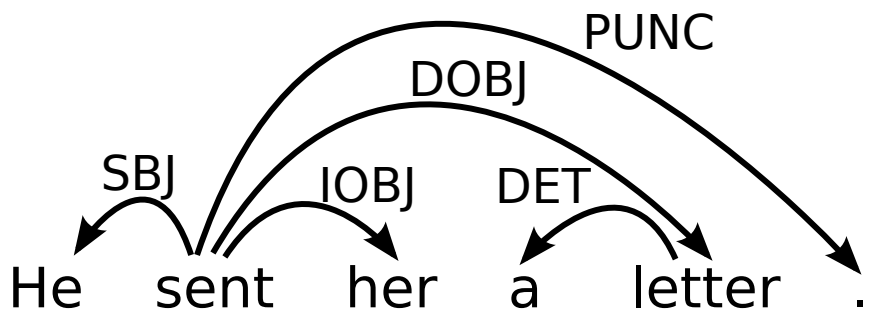
Arcs

He $\overset{\text{SBJ}}{\longleftarrow}$ sent

sent $\overset{\text{IOBJ}}{\longrightarrow}$ her

a $\overset{\text{DET}}{\longleftarrow}$ letter

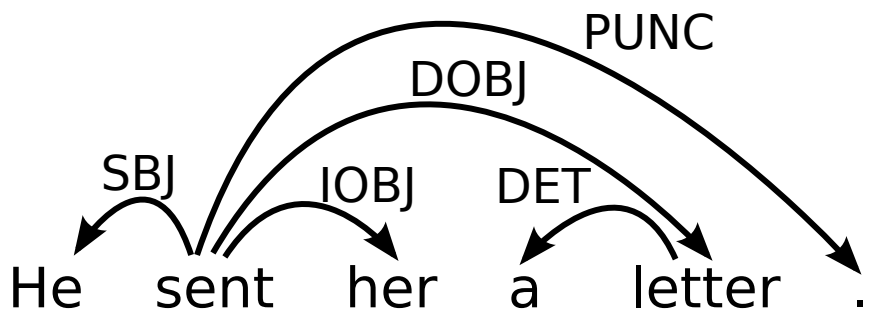
sent $\overset{\text{DOBJ}}{\longrightarrow}$ letter



Parse Example

Transitions: SH-LA-SH-RA-SH-LA-RE-RA-RE

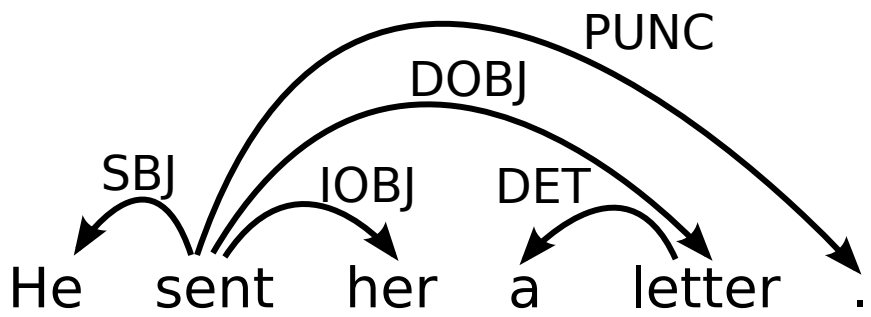
Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[.]_B$	He $\xleftarrow{\text{SBJ}}$ sent
		sent $\xrightarrow{\text{IOBJ}}$ her
		a $\xleftarrow{\text{DET}}$ letter
		sent $\xrightarrow{\text{DOBJ}}$ letter



Parse Example

Transitions: SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

Stack	**Buffer**	**Arcs**
$[\text{sent}, .]_S$	$[\,]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent
		sent $\overset{\text{IOBJ}}{\rightarrow}$ her
		a $\overset{\text{DET}}{\leftarrow}$ letter
		sent $\overset{\text{DOBJ}}{\rightarrow}$ letter
		sent $\overset{\text{PUNC}}{\rightarrow}$.



Classifier

- To guide the parser we use a (linear) classifier:

$$t^* = \underset{t}{\text{argmax}}\, \mathbf{w} \cdot \mathbf{f}(c, t)$$

- History-based feature representation $\mathbf{f}(c, t)$:
  - Features over input tokens relative to S and B
  - Features over the (partial) dependency tree defined by A
  - Features over the (partial) transition sequence
- Weight vector $\mathbf{w}$ learned from treebank data

Deterministic Parsing

PARSE($w_1, \ldots, w_n$, $\mathbf{w}$)
1 $c \leftarrow ([\,]_S, [w_1, \ldots, w_n]_B, \{\,\})$
2 **while** $B_c \neq [\,]$
3 $t^* \leftarrow \text{argmax}_t\, \mathbf{w} \cdot \mathbf{f}(c, t)$
4 $c \leftarrow t^*(c)$
5 **return** $T = (\{w_1, \ldots, w_n\}, A_c)$

Online Learning with an Oracle

LEARN($\{T_1, \ldots, T_N\}$)

1 **w** $\leftarrow 0.0$
2 **for** i in $1..K$
3 **for** j in $1..N$
4 $c \leftarrow ([\,]_S, [w_1, \ldots, w_{n_j}]_B, \{\,\})$
5 **while** $B_c \neq [\,]$
6 $t^* \leftarrow \text{argmax}_t \, \mathbf{w} \cdot \mathbf{f}(c, t)$
7 $t_o \leftarrow o(c, T_i)$
8 **if** $t^* \neq t_o$
9 $\mathbf{w} \leftarrow \mathbf{w} + \mathbf{f}(c, t_o) - \mathbf{f}(c, t^*)$
10 $c \leftarrow t_o(c)$
11 **return w**

Online Learning with an Oracle

LEARN($\{T_1, \ldots, T_N\}$)

```
 1   w ← 0.0
 2   for i in 1..K
 3       for j in 1..N
 4           c ← ([ ]_S, [w_1, ..., w_{n_j}]_B, { })
 5           while B_c ≠ [ ]
 6               t* ← argmax_t w · f(c, t)
 7               t_o ← o(c, T_i)
 8               if t* ≠ t_o
 9                   w ← w + f(c, t_o) − f(c, t*)
10               c ← t_o(c)
11   return w
```

- Oracle $o(c, T_i)$ returns the optimal transition for c and T_i

Standard Oracle for Arc-Eager Parsing

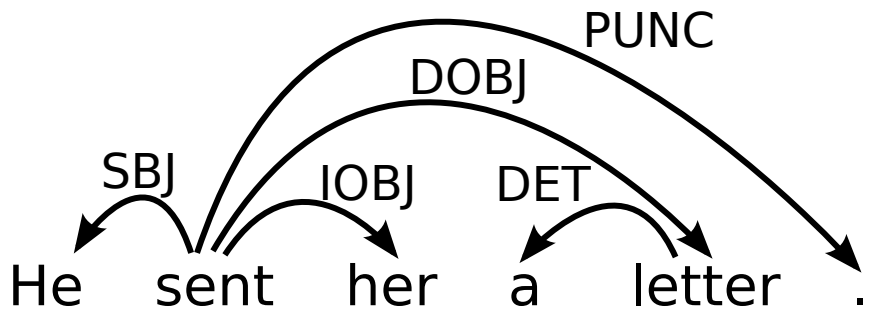
$$o(c, T) = \begin{cases} \text{Left-Arc} & \text{if top}(S_c) \leftarrow \text{first}(B_c) \text{ in } T \\ \text{Right-Arc} & \text{if top}(S_c) \rightarrow \text{first}(B_c) \text{ in } T \\ \text{Reduce} & \text{if } \exists w < \text{top}(S_c) : w \leftrightarrow \text{first}(B_c) \text{ in } T \\ \text{Shift} & \text{otherwise} \end{cases}$$

- Correct:
  - Derives T in a configuration sequence $C(o, T) = c_0, \ldots, c_m$
- Problems:
  - Deterministic: Ignores other derivations of T
  - Incomplete: Valid only for configurations in $C(o, T)$

Non-Determinism

Transitions: SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

Stack	**Buffer**	**Arcs**
$[\,]_S$	[He, sent, her, a, letter, .]$_B$	



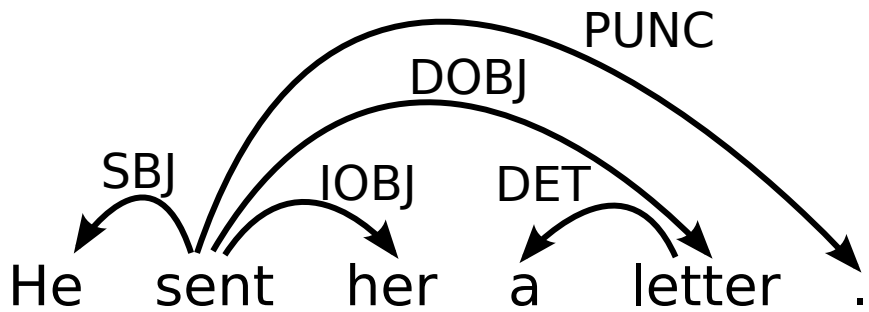
Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH

Stack	**Buffer**	**Arcs**
$[\text{He}]_S$	$[\text{sent, her, a, letter, .}]_B$	



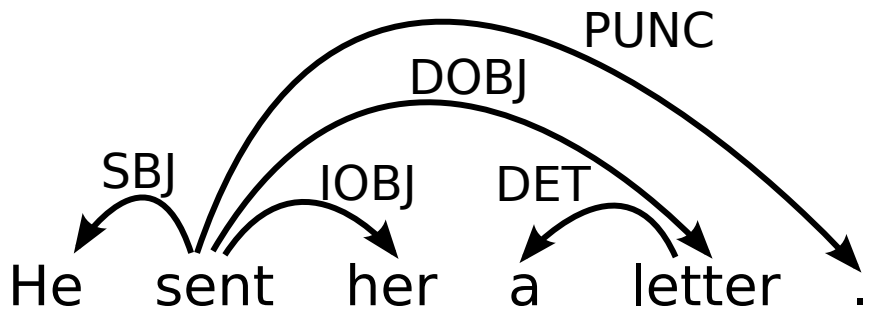
Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA

Stack	**Buffer**	**Arcs**
$[\ ]_S$	$[\text{sent, her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



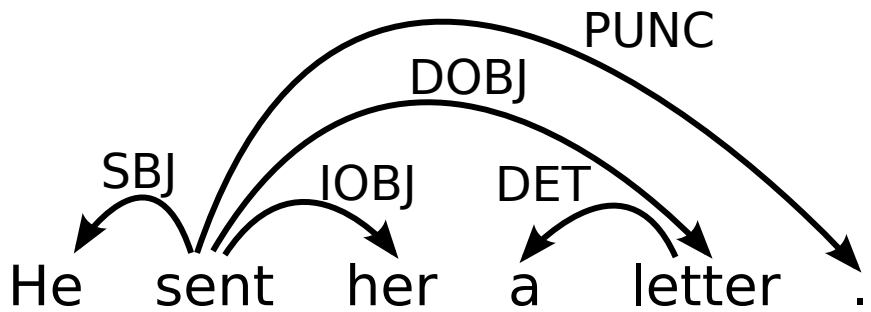
Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH

Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[\text{her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\longleftarrow}$ sent



Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH-RA

Stack

$[\text{sent, her}]_S$

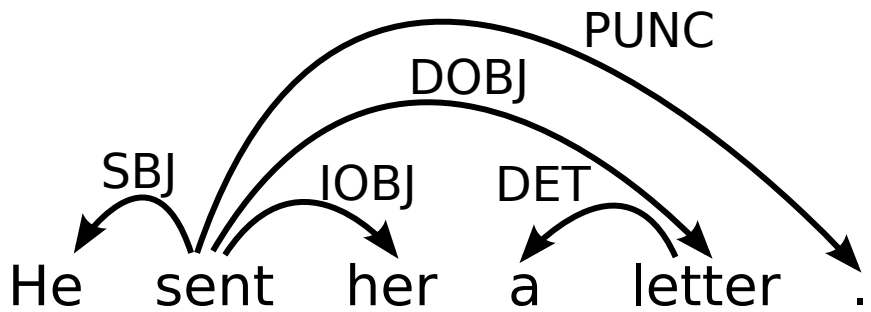
Buffer

$[\text{a, letter, .}]_B$

Arcs

He $\xleftarrow{\text{SBJ}}$ sent

sent $\xrightarrow{\text{IOBJ}}$ her



Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH-RA-RE

Stack

$[\text{sent}]_S$

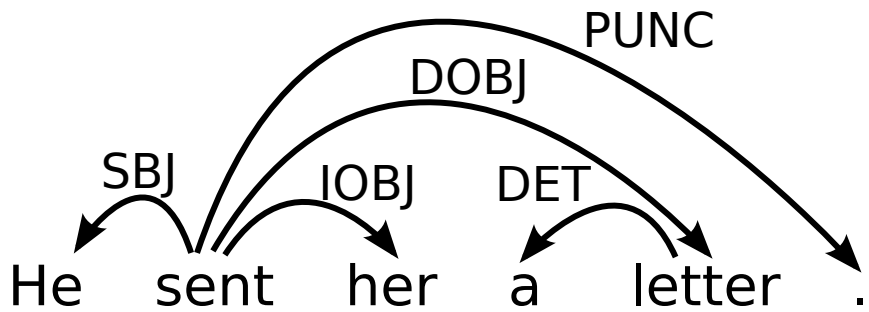
Buffer

$[\text{a, letter, .}]_B$

Arcs

He $\xleftarrow{\text{SBJ}}$ sent

sent $\xrightarrow{\text{IOBJ}}$ her



Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH-RA-RE-SH

Stack

$[\text{sent, a}]_S$

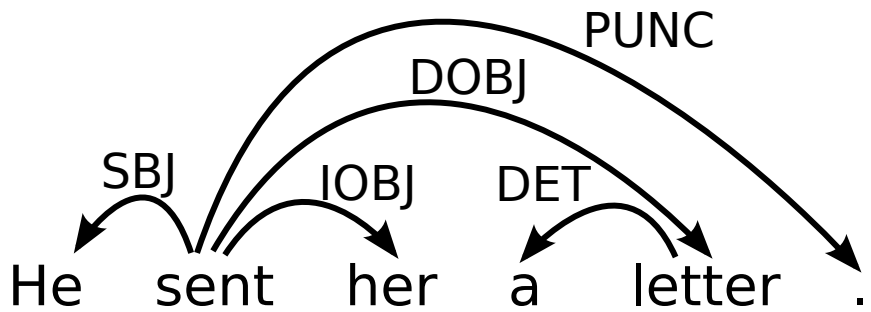
Buffer

$[\text{letter, .}]_B$

Arcs

He $\xleftarrow{\text{SBJ}}$ sent

sent $\xrightarrow{\text{IOBJ}}$ her



Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH-RA-RE-SH-LA

Stack

$[\text{sent}]_S$

Buffer

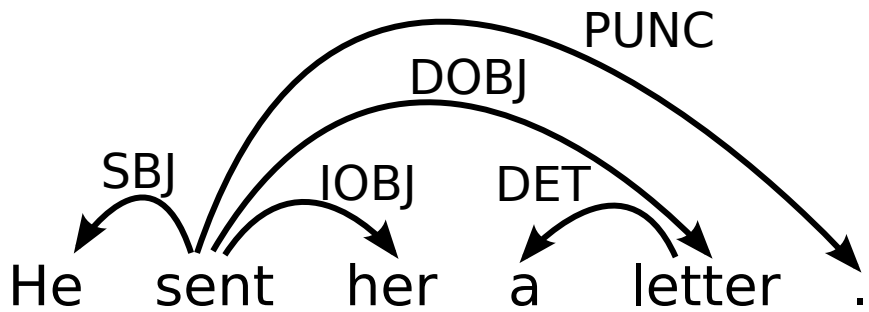
$[\text{letter}, .]_B$

Arcs

He $\overset{\text{SBJ}}{\leftarrow}$ sent

sent $\overset{\text{IOBJ}}{\rightarrow}$ her

a $\overset{\text{DET}}{\leftarrow}$ letter



Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH-RA-RE-SH-LA-RA

Stack

$[\text{sent, letter}]_S$

Buffer

$[.]_B$

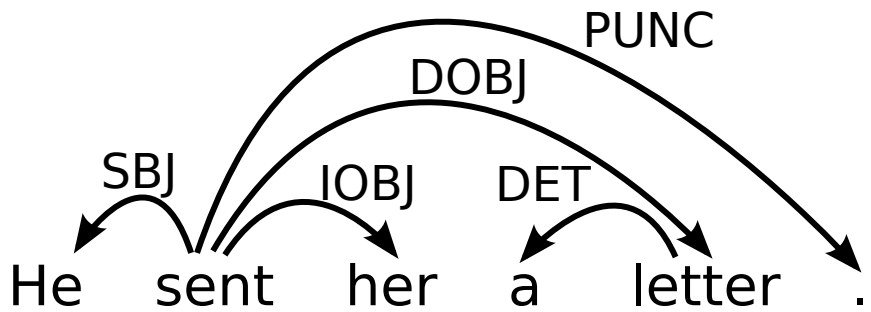
Arcs

He $\xleftarrow{\text{SBJ}}$ sent

sent $\xrightarrow{\text{IOBJ}}$ her

a $\xleftarrow{\text{DET}}$ letter

sent $\xrightarrow{\text{DOBJ}}$ letter



Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH-RA-RE-SH-LA-RA-RE

Stack

$[\text{sent}]_S$

Buffer

$[.]_B$

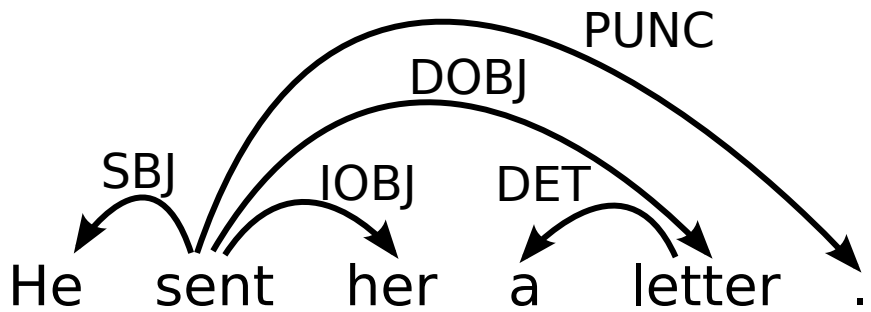
Arcs

He $\xleftarrow{\text{SBJ}}$ sent

sent $\xrightarrow{\text{IOBJ}}$ her

a $\xleftarrow{\text{DET}}$ letter

sent $\xrightarrow{\text{DOBJ}}$ letter



Non-Determinism

Transitions:

SH-LA-SH-RA-SH-LA-RE-RA-RE-RA

SH-LA-SH-RA-RE-SH-LA-RA-RE-RA

Stack

$[\text{sent}, .]_S$

Buffer

$[\ ]_B$

Arcs

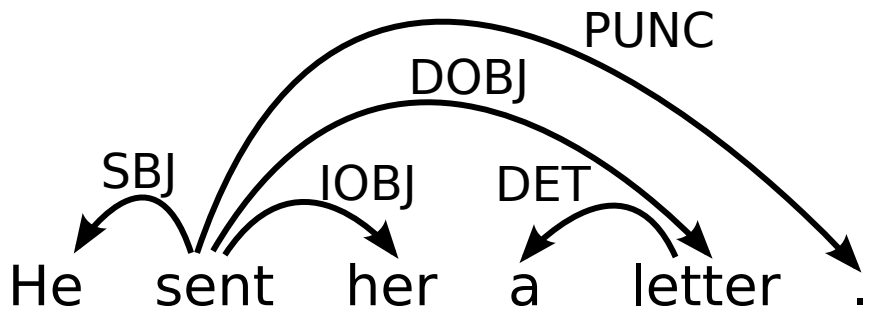
He $\xleftarrow{\text{SBJ}}$ sent

sent $\xrightarrow{\text{IOBJ}}$ her

a $\xleftarrow{\text{DET}}$ letter

sent $\xrightarrow{\text{DOBJ}}$ letter

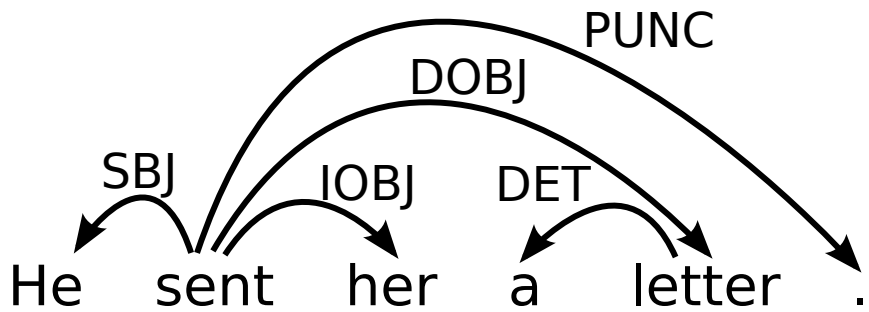
sent $\xrightarrow{\text{PUNC}}$.



Non-Optimality

Transitions:

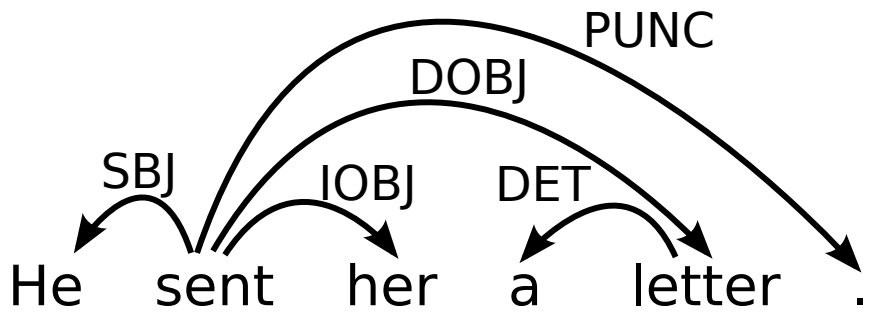
Stack	**Buffer**	**Arcs**
$[\,]_S$	[He, sent, her, a, letter, .]$_B$	



Non-Optimality

Transitions: SH

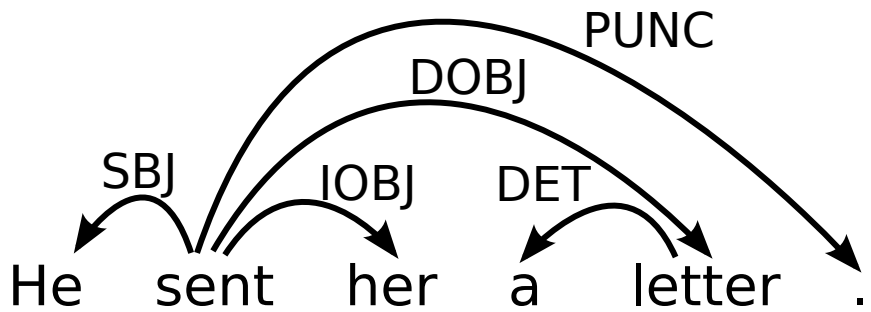
Stack	**Buffer**	**Arcs**
$[\text{He}]_S$	$[\text{sent, her, a, letter, .}]_B$	



Non-Optimality

Transitions: SH-LA

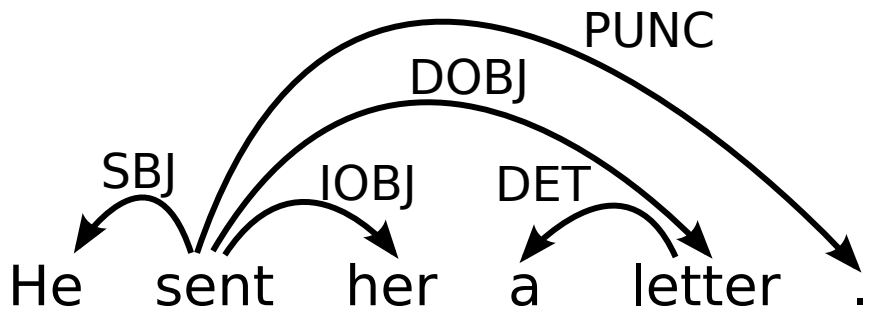
Stack	**Buffer**	**Arcs**
$[\ ]_S$	$[\text{sent, her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



Non-Optimality

Transitions: SH-LA-SH

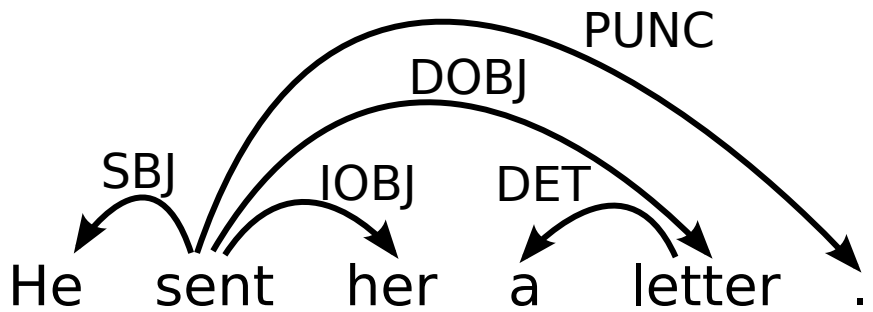
Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[\text{her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



Non-Optimality

Transitions: SH-LA-SH-SH

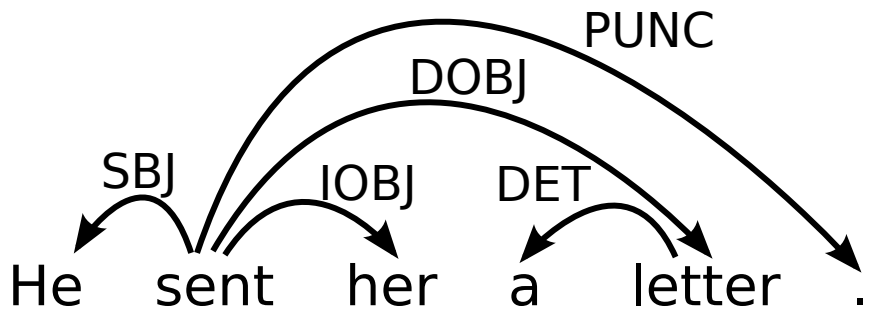
Stack	**Buffer**	**Arcs**
$[\text{sent, her}]_S$	$[\text{a, letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



Non-Optimality

Transitions: SH-LA-SH-SH-SH

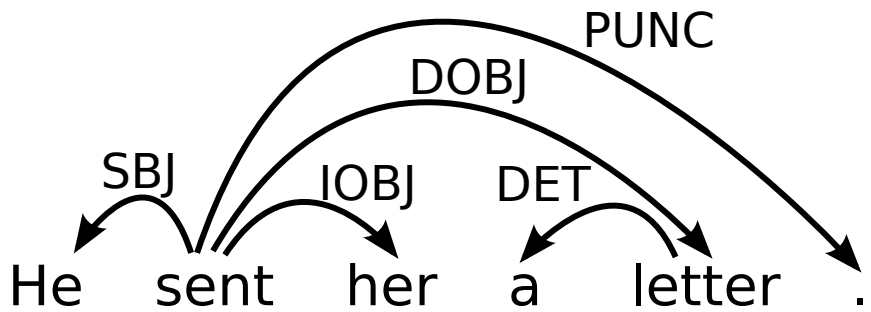
Stack	**Buffer**	**Arcs**
$[\text{sent}, \text{her}, \text{a}]_S$	$[\text{letter}, .]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



Non-Optimality

Transitions: SH-LA-SH-SH-SH-LA

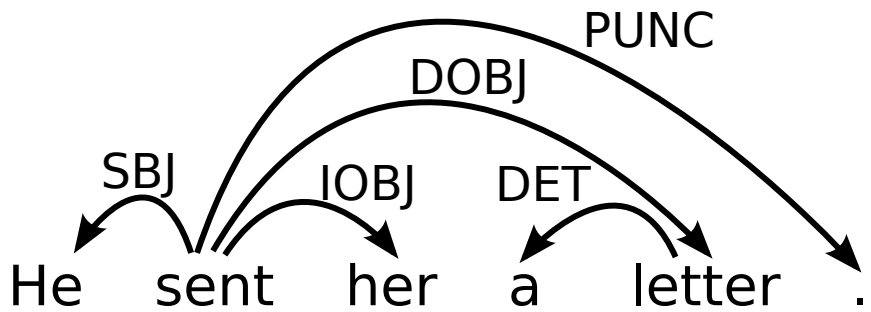
Stack	**Buffer**	**Arcs**
$[\text{sent}, \text{her}]_S$	$[\text{letter}, .]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent a $\overset{\text{DET}}{\leftarrow}$ letter



Non-Optimality

Transitions: SH-LA-SH-SH-SH-LA-SH

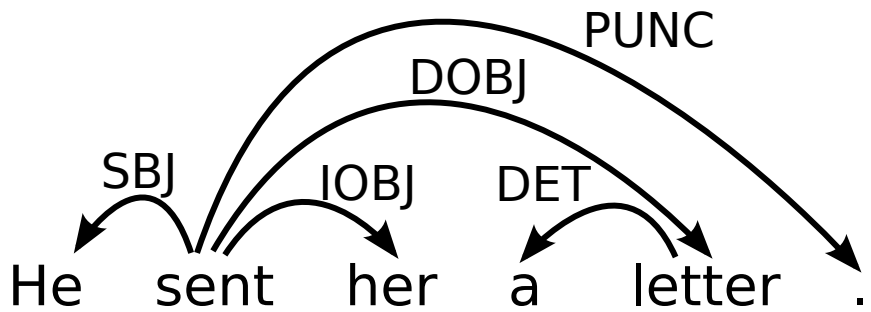
Stack	**Buffer**	**Arcs**
$[\text{sent, her, letter}]_S$	$[.]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent a $\overset{\text{DET}}{\leftarrow}$ letter



Non-Optimality

Transitions: SH-LA-SH-SH-SH-LA-SH-SH [2/5]

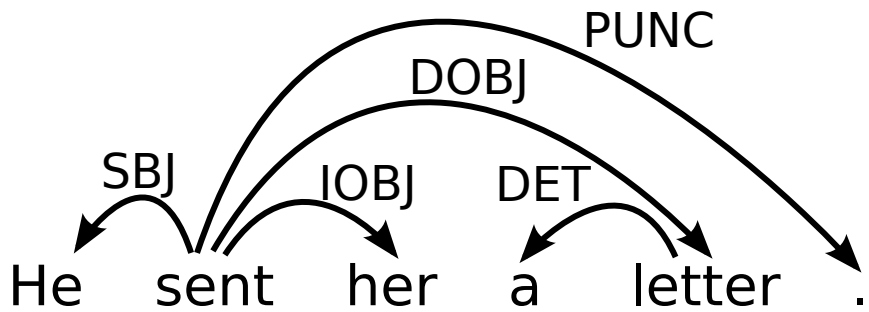
Stack	**Buffer**	**Arcs**
$[\text{sent, her, letter, .}]_S$	$[\ ]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent a $\overset{\text{DET}}{\leftarrow}$ letter



Non-Optimality

Transitions: SH-LA-SH-SH-SH-LA-SH-SH [2/5]

Stack	**Buffer**	**Arcs**
$[\ ]_S$	[He, sent, her, a, letter, .]$_B$	

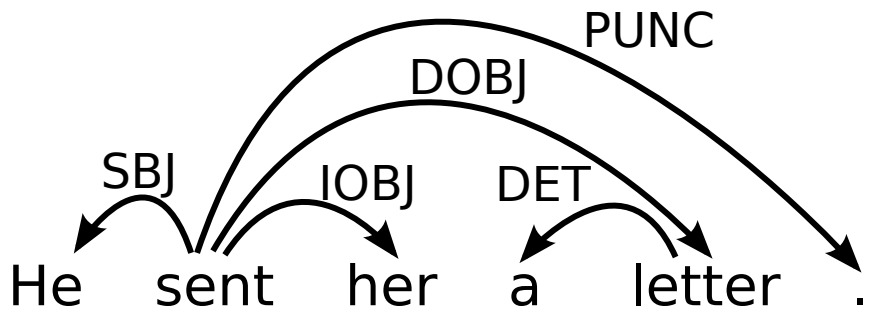


Non-Optimality

Transitions: SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH

Stack	**Buffer**	**Arcs**
$[\text{He}]_S$	$[\text{sent, her, a, letter, .}]_B$	



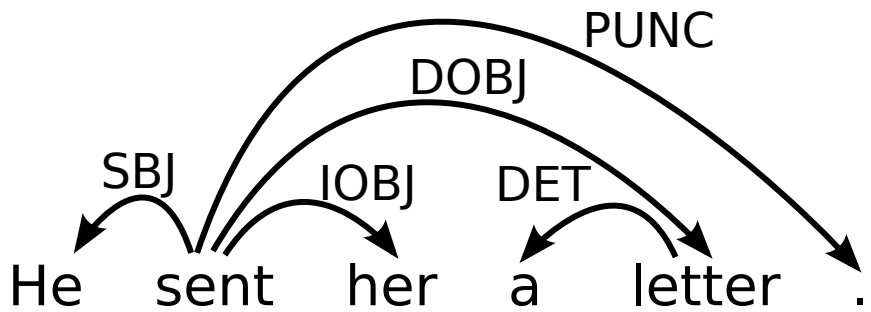
Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA

Stack	**Buffer**	**Arcs**
$[\ ]_S$	$[\text{sent, her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



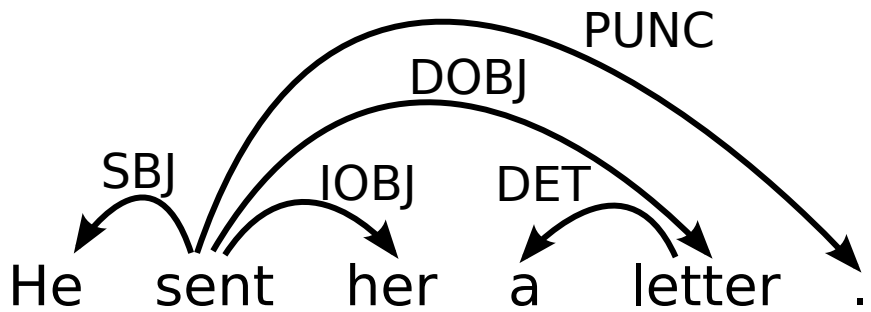
Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH

Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[\text{her, a, letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



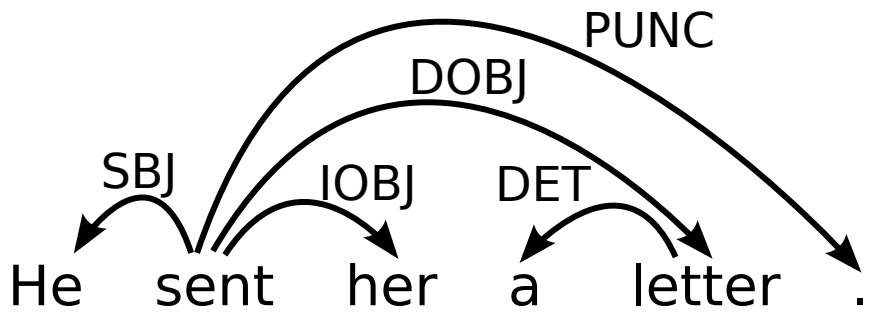
Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH-SH

Stack	**Buffer**	**Arcs**
$[\text{sent, her}]_S$	$[\text{a, letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



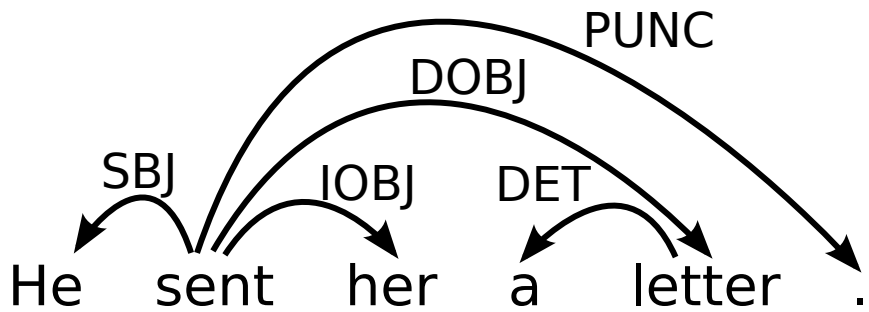
Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH-SH-SH

Stack	**Buffer**	**Arcs**
$[\text{sent, her, a}]_S$	$[\text{letter, .}]_B$	He $\overset{\text{SBJ}}{\leftarrow}$ sent



Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH-SH-SH-LA

Stack

$[\text{sent, her}]_S$

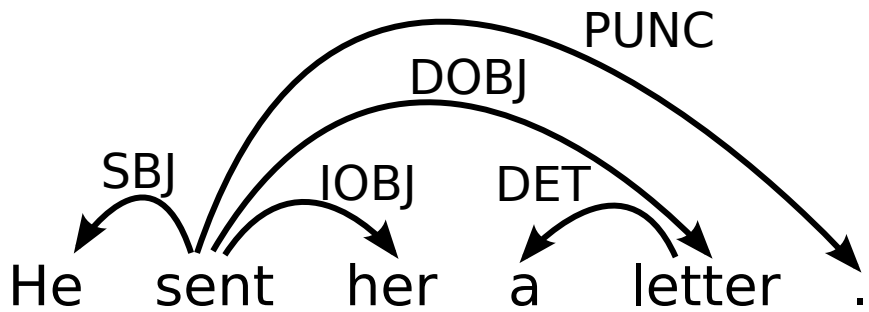
Buffer

$[\text{letter, .}]_B$

Arcs

He $\overset{\text{SBJ}}{\leftarrow}$ sent

a $\overset{\text{DET}}{\leftarrow}$ letter



Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH-SH-SH-LA-LA

Stack

$[\text{sent}]_S$

Buffer

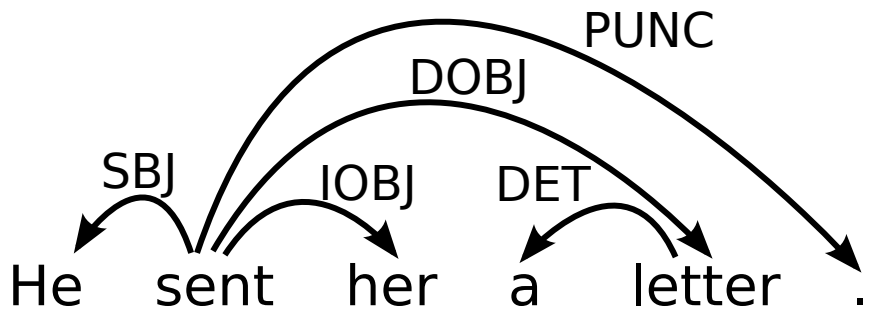
$[\text{letter}, .]_B$

Arcs

He $\overset{\text{SBJ}}{\leftarrow}$ sent

a $\overset{\text{DET}}{\leftarrow}$ letter

her $\overset{\text{X}}{\leftarrow}$ letter



Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH-SH-SH-LA-LA-RA

Stack

$[\text{sent, letter}]_S$

Buffer

$[.]_B$

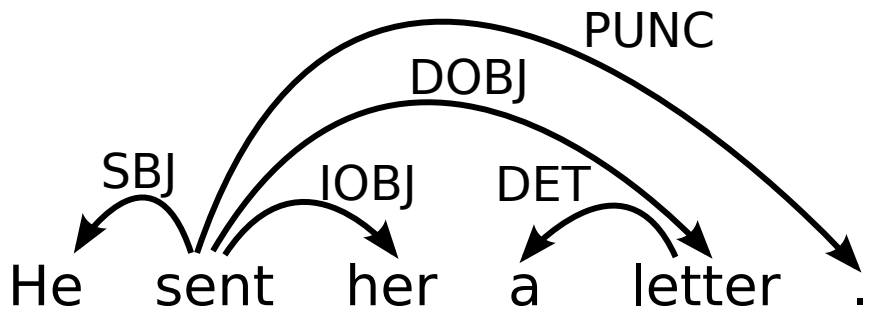
Arcs

He $\overset{\text{SBJ}}{\longleftarrow}$ sent

a $\overset{\text{DET}}{\longleftarrow}$ letter

her $\overset{\text{X}}{\longleftarrow}$ letter

sent $\overset{\text{DOBJ}}{\longrightarrow}$ letter



Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH-SH-SH-LA-LA-RA-RE

Stack

$[\text{sent}]_S$

Buffer

$[.]_B$

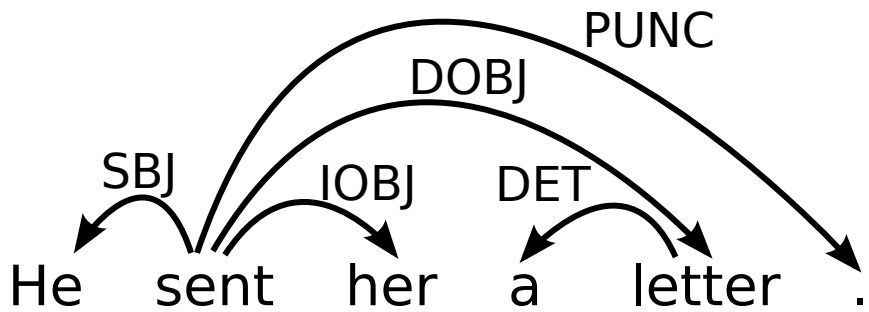
Arcs

He $\overset{\text{SBJ}}{\longleftarrow}$ sent

a $\overset{\text{DET}}{\longleftarrow}$ letter

her $\overset{\text{X}}{\longleftarrow}$ letter

sent $\overset{\text{DOBJ}}{\longrightarrow}$ letter



Non-Optimality

Transitions:

SH-LA-SH-SH-SH-LA-SH-SH [2/5]

SH-LA-SH-SH-SH-LA-LA-RA-RE-RA [4/5]

Stack

$[\text{sent}, .]_S$

Buffer

$[\ ]_B$

Arcs

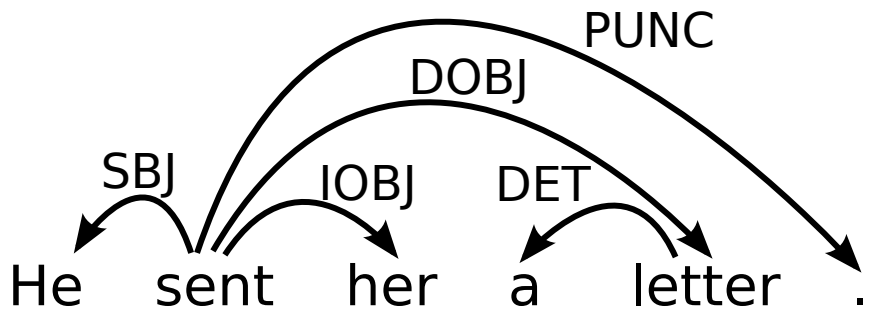
He $\overset{\text{SBJ}}{\longleftarrow}$ sent

a $\overset{\text{DET}}{\longleftarrow}$ letter

her $\overset{\text{X}}{\longleftarrow}$ letter

sent $\overset{\text{DOBJ}}{\longrightarrow}$ letter

sent $\overset{\text{PUNC}}{\longrightarrow}$.



Rethinking Oracles

- New idea:
  - A transition is optimal if the best tree remains reachable
  - Best tree = $\text{argmin}_{T'} \mathcal{L}(T, T')$
- New view of oracle:
  - Boolean function $o(c, t, T) =$ **true** if t is optimal for c and T
  - Non-deterministic: More than one transition can be optimal
  - Complete: Correct for all configurations
- New problem:
  - How do we know which trees are reachable?

Reachability for Arcs and Trees

- Arc reachability:
  - An arc $w_i \rightarrow w_j$ is reachable in c iff $w_i \rightarrow w_j \in A_c$, or $w_i \in S_c \cup B_c$ and $w_j \in B_c$ (same for $w_i \leftarrow w_j$)
- Tree reachability:
  - A (projective) tree T is reachable in c iff every arc in T is reachable in c
- Arc-decomposable system:
  - Tree reachability reduces to arc reachability
  - Holds for some transition systems but not all

A New Oracle

$$\mathcal{R}(c) \equiv \{a \mid a \text{ is an arc reachable in } c\}$$

$$o(c,t,T) = \begin{cases} \textbf{true} & \text{if } [\mathcal{R}(c) - \mathcal{R}(t(c))] \cap T = \emptyset \\ \textbf{false} & \text{otherwise} \end{cases}$$

Case by Case

- Notation: s = word on top of stack, b = first word in buffer

$$o(c, \mathrm{LA}, T) = \begin{cases} \textbf{false} & \text{if } \exists w \in B_c : s \leftrightarrow w \in T \text{ (except } s \leftarrow b) \\ \textbf{true} & \text{otherwise} \end{cases}$$

$$o(c, \mathrm{RA}, T) = \begin{cases} \textbf{false} & \text{if } \exists w \in S_c : w \leftrightarrow b \in T \text{ (except } s \rightarrow b) \\ \textbf{true} & \text{otherwise} \end{cases}$$

$$o(c, \mathrm{RE}, T) = \begin{cases} \textbf{false} & \text{if } \exists w \in B_c : s \rightarrow w \in T \\ \textbf{true} & \text{otherwise} \end{cases}$$

$$o(c, \mathrm{SH}, T) = \begin{cases} \textbf{false} & \text{if } \exists w \in S_c : w \leftrightarrow b \in T \\ \textbf{true} & \text{otherwise} \end{cases}$$

A New Learning Algorithm

LEARN($\{T_1, \ldots, T_N\}$)
1 **w** $\leftarrow 0.0$
2 **for** i in $1..K$
3 **for** j in $1..N$
4 $c \leftarrow ([\,]_S, [w_1, \ldots, w_{n_j}]_B, \{\,\})$
5 **while** $B_c \neq [\,]$
6 $t^* \leftarrow \text{argmax}_t \, \mathbf{w} \cdot \mathbf{f}(c, t)$
7 $t_o \leftarrow \text{argmax}_{t \in \{t \mid o(c,t,T_i)\}} \, \mathbf{w} \cdot \mathbf{f}(c, t)$
8 **if** $t^* \neq t_o$
9 $\mathbf{w} \leftarrow \mathbf{w} + \mathbf{f}(c, t_o) - \mathbf{f}(c, t^*)$
10 $c \leftarrow \text{CHOICE}(t_o(c), t^*(c))$
11 **return w**

A New Learning Algorithm

LEARN($\{T_1, \ldots, T_N\}$)
1 **w** $\leftarrow 0.0$
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4 $c \leftarrow ([\,]_S, [w_1, \ldots, w_{n_j}]_B, \{\,\})$
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6 $t^* \leftarrow \text{argmax}_t\, \mathbf{w} \cdot \mathbf{f}(c, t)$
7 $t_o \leftarrow \text{argmax}_{t \in \{t \mid o(c,t,T_i)\}}\, \mathbf{w} \cdot \mathbf{f}(c, t)$
8 **if** $t^* \neq t_o$
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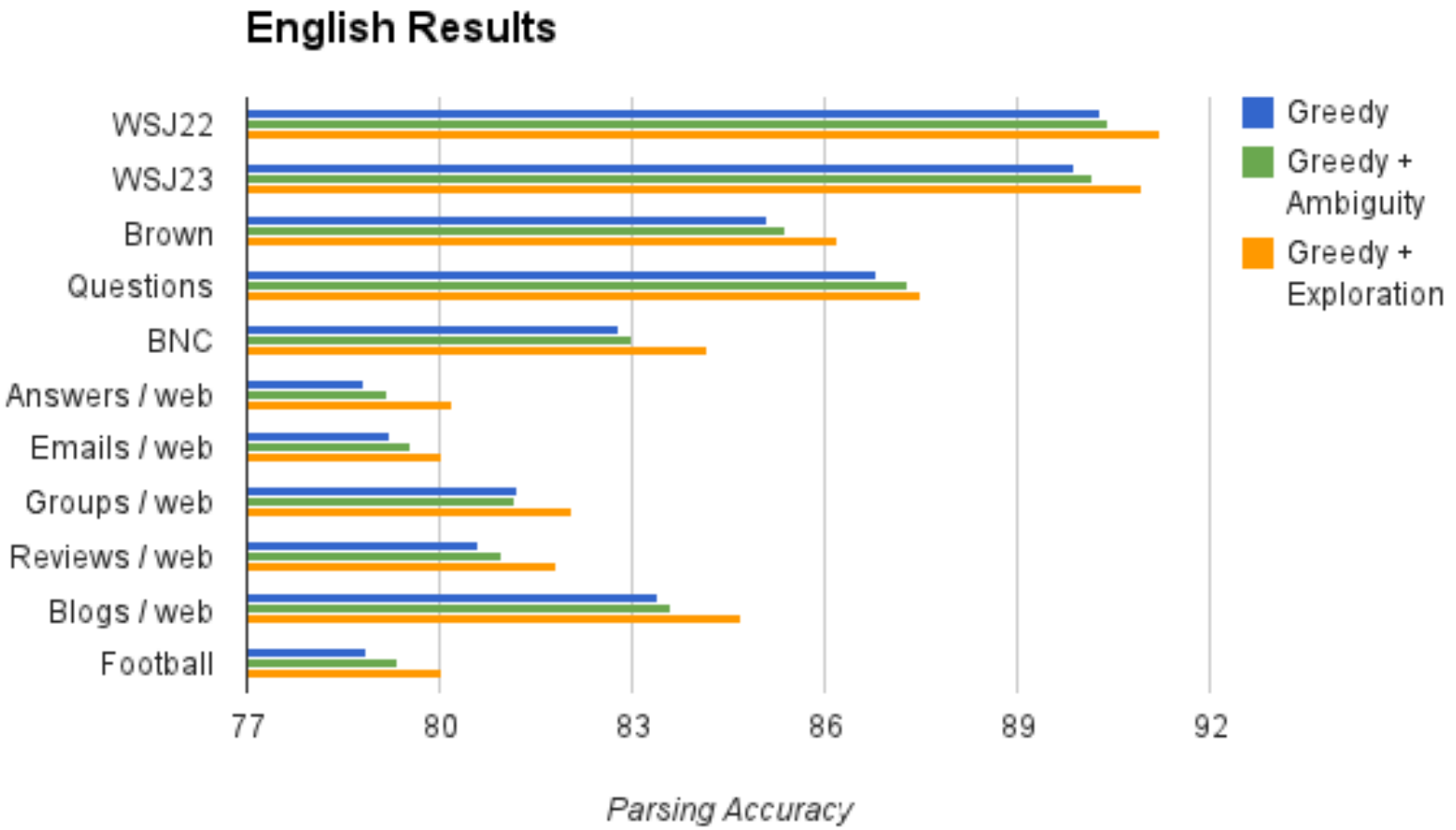
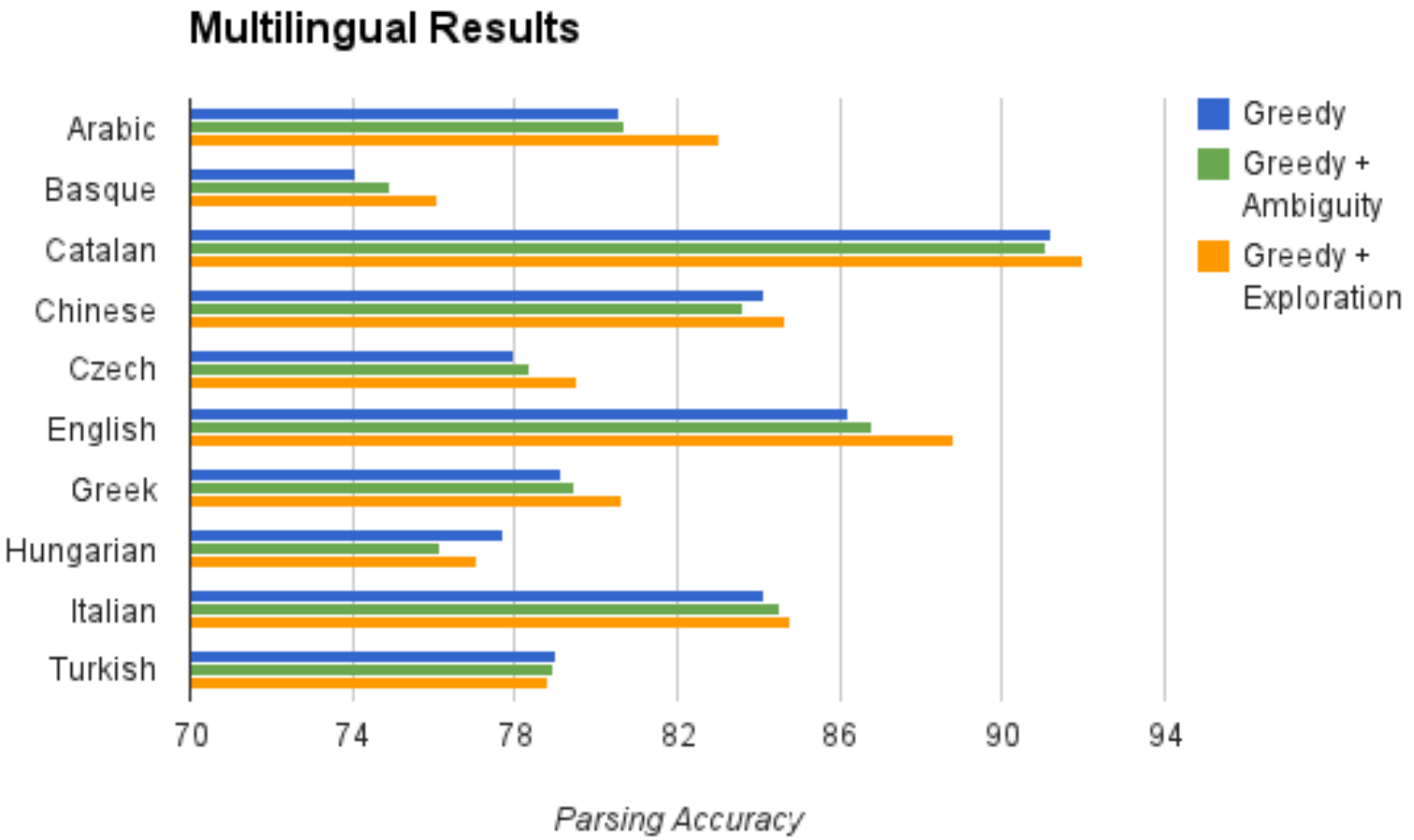
10 $c \leftarrow \text{CHOICE}(t_o(c), t^*(c))$
11 **return w**

Experimental Evaluation

- Data sets:
  - English treebanks: WSJ, Brown, BNC, Google Web
  - Multilingual: CoNLL 2007 Shared Task
- Settings:
  - Greedy: Old learning algorithm
  - Greedy + Ambiguity: $\textsc{choice}(t_o(c), t^*(c)) = t_o(c)$
  - Greedy + Exploration: Random $\textsc{choice}(t_o(c), t^*(c))$


English Results
WSJ22
WSJ23
Brown
Questions
BNC
Answers / web
Emails / web
Groups / web
Reviews / web
Blogs / web
Football
77
80
83
86
89
92
Parsing Accuracy
Greedy
Greedy + Ambiguity
Greedy + Exploration


Multilingual Results
Arabic
Basque
Catalan
Chinese
Czech
English
Greek
Hungarian
Italian
Turkish
70
74
78
82
86
90
94
Parsing Accuracy
Greedy
Greedy + Ambiguity
Greedy + Exploration

Conclusion

- Exploring a larger search space at training time helps
  - Allowing non-canonical derivations (spurious ambiguity)
  - Learning optimal transitions in non-optimal configurations
- Requires a new type of oracle
  - Non-deterministic: more than one transition may be optimal
  - Complete: optimality defined for all configurations
- Parsing remains deterministic (fast)