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Training Deterministic Parsers Using Non-Deterministic Oracles

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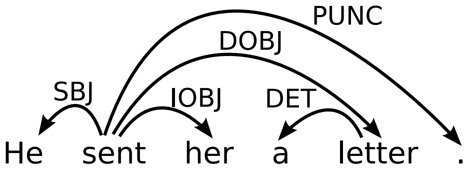
Introduction



- 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

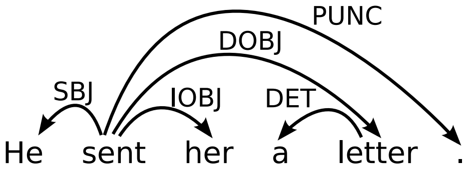
- Transition-based dependency parsing:
  - Define a transition system for dependency parsing
  - Train a classifier for predicting the next transition
  - Use the classifier to do deterministic parsing
- Current practice:
  - Train classifier on derivations produced by an oracle
  - Leads to error propagation 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

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

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

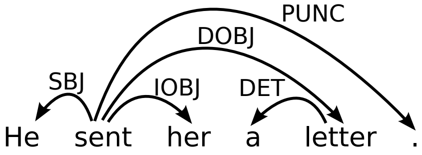
$$\text{Reduce}\ \frac{([\ldots, w_i]_S,\ B,\ A)}{([\ldots]_S,\ B,\ A)}\ \text{HEAD}(w_i)$$

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

Parse Example

Transitions:

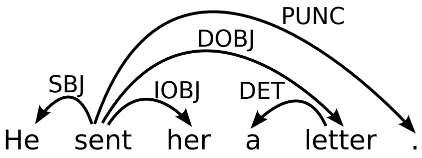
Stack	**Buffer**	**Arcs**
$[\ ]_S$	$[$He, sent, her, a, letter, .$]_B$	



Parse Example

Transitions: SH

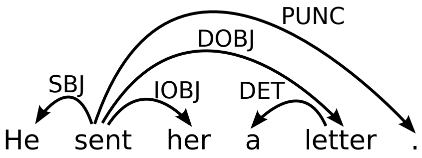
Stack	**Buffer**	**Arcs**
$[\text{He}]_S$	$[\text{sent, her, a, letter, .}]_B$	



Parse Example

Transitions: SH-LA

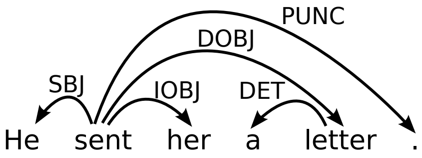
Stack	**Buffer**	**Arcs**
$[\ ]_S$	$[\text{sent, her, a, letter, .}]_B$	He $\xleftarrow{\text{SBJ}}$ sent



Parse Example

Transitions: SH-LA-SH

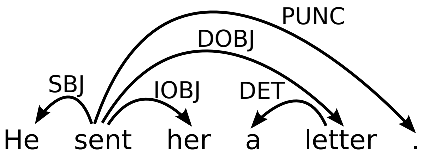
Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[\text{her, a, letter, .}]_B$	$\text{He} \xleftarrow{\text{SBJ}} \text{sent}$



Parse Example

Transitions: SH-LA-SH-RA

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



Parse Example

Transitions: SH-LA-SH-RA-SH

Stack

[sent, her, a]$_S$

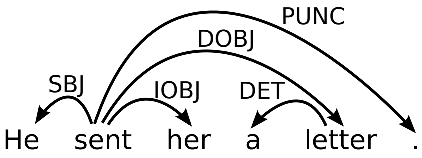
Buffer

[letter, .]$_B$

Arcs

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

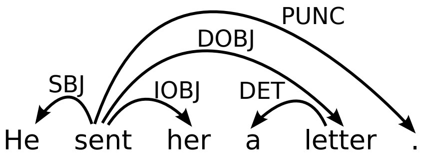
sent $\xrightarrow{\text{IOBJ}}$ her



Parse Example

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

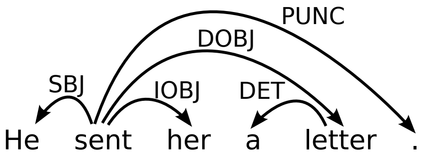
Stack	Buffer	Arcs
$[\text{sent}, \text{her}]_S$	$[\text{letter}, .]_B$	He $\xleftarrow{\text{SBJ}}$ sent sent $\xrightarrow{\text{IOBJ}}$ her a $\xleftarrow{\text{DET}}$ letter



Parse Example

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

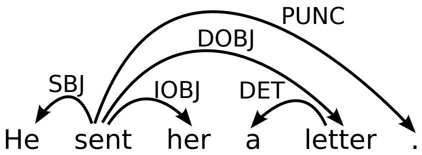
Stack	**Buffer**	**Arcs**
$[\text{sent}]_S$	$[\text{letter}, .]_B$	$\text{He} \xleftarrow{\text{SBJ}} \text{sent}$
		$\text{sent} \xrightarrow{\text{IOBJ}} \text{her}$
		$\text{a} \xleftarrow{\text{DET}} \text{letter}$



Parse Example

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

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

Stack

$[\text{sent}]_S$

Buffer

$[.]_B$

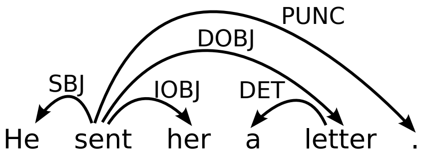
Arcs

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

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

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

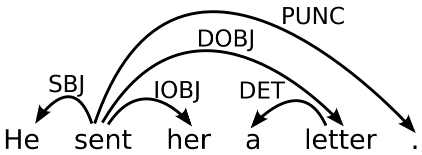
sent $\xrightarrow{\text{DOBJ}}$ letter



Parse Example

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

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



Classifier

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

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

- 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

$\textsc{Parse}(w_1, \ldots, w_n, \mathbf{w})$

$\quad c \leftarrow ([\,]_S, [w_1, \ldots, w_n]_B, \{\,\})$

$\quad \textbf{while } B_c \neq [\,]$

$\qquad t^* \leftarrow \text{argmax}_t\, \mathbf{w} \cdot \mathbf{f}(c, t)$

$\qquad c \leftarrow t^*(c)$

$\quad \textbf{return } T = (\{w_1, \ldots, w_n\}, A_c)$

Online Learning with an Oracle

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

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

Online Learning with an Oracle

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

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

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

Standard Oracle for Arc-Eager Parsing

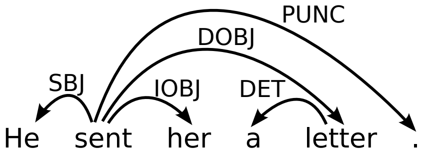
$$o(c, T) = \begin{cases} \text{Left-Arc} & \text{if top}(S_c) \leftarrow \text{first}(B_c) \text{ in } T \\ \text{Right-Arc} & \text{if top}(S_c) \rightarrow \text{first}(B_c) \text{ in } T \\ \text{Reduce} & \text{if } \exists w < \text{top}(S_c) : w \leftrightarrow \text{first}(B_c) \text{ in } T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

- 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, .$]_B$	

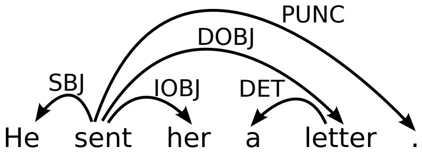


Non-Determinism

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

SH

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



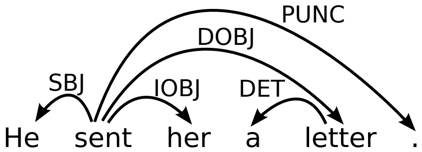
Non-Determinism

Transitions:

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

SH-LA

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



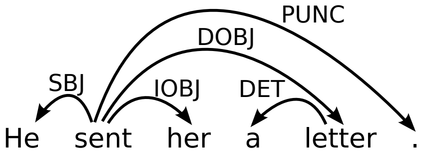
Non-Determinism

Transitions:

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

SH-LA-SH

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



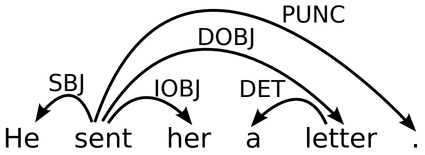
Non-Determinism

Transitions:

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

SH-LA-SH-RA

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



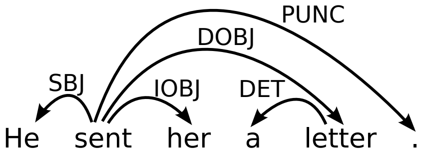
Non-Determinism

Transitions:

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

SH-LA-SH-RA-RE

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



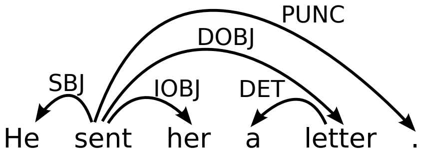
Non-Determinism

Transitions:

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

SH-LA-SH-RA-RE-SH

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



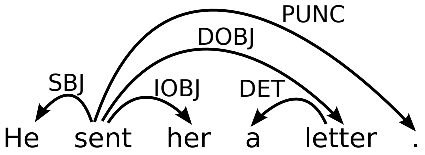
Non-Determinism

Transitions:

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

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

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

$[.]_B$

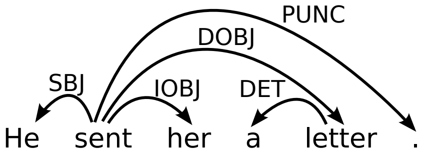
Arcs

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

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

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

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



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

$[.]_B$

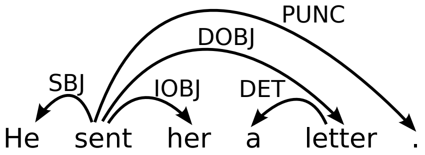
Arcs

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

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

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

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



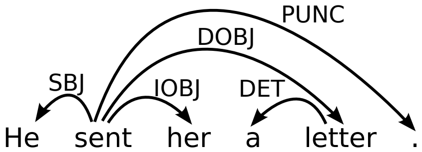
Non-Determinism

Transitions:

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

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

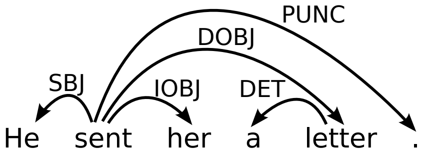
Stack	**Buffer**	**Arcs**
$[\text{sent}, .]_S$	$[\ ]_B$	He $\xleftarrow{\text{SBJ}}$ sent
		sent $\xrightarrow{\text{IOBJ}}$ her
		a $\xleftarrow{\text{DET}}$ letter
		sent $\xrightarrow{\text{DOBJ}}$ letter
		sent $\xrightarrow{\text{PUNC}}$.



Non-Optimality

Transitions:

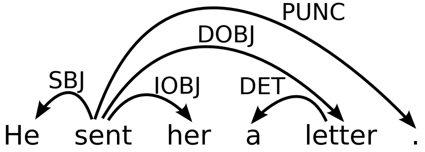
Stack	**Buffer**	**Arcs**
$[\ ]_S$	$[$He, sent, her, a, letter, .$]_B$	



Non-Optimality

Transitions: SH

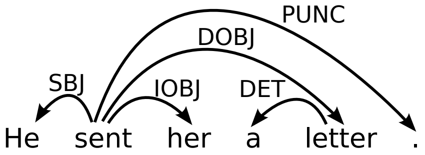
Stack	**Buffer**	**Arcs**
$[\text{He}]_S$	$[\text{sent, her, a, letter, .}]_B$	



Non-Optimality

Transitions: SH-LA

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



Non-Optimality

Transitions: SH-LA-SH

Stack

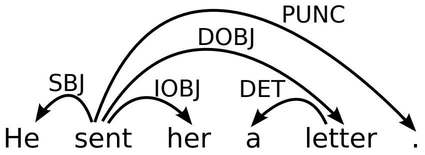
$[\text{sent}]_S$

Buffer

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

Arcs

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



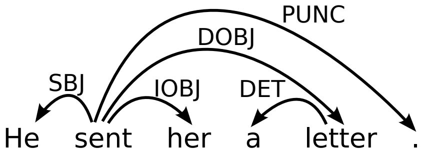
Non-Optimality

Transitions: SH-LA-SH-SH

Stack [sent, her]$_S$

Buffer [a, letter, .]$_B$

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



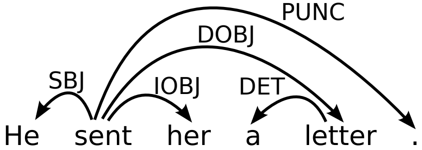
Non-Optimality

Transitions: SH-LA-SH-SH-SH

Stack [sent, her, a]$_S$

Buffer [letter, .]$_B$

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



Non-Optimality

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

Stack

[sent, her]$_S$

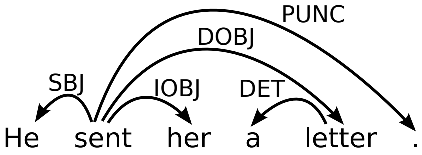
Buffer

[letter, .]$_B$

Arcs

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

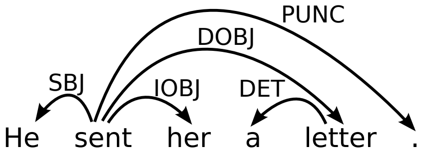
a $\xleftarrow{\text{DET}}$ letter



Non-Optimality

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

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



Non-Optimality

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

Stack

[sent, her, letter, .]$_S$

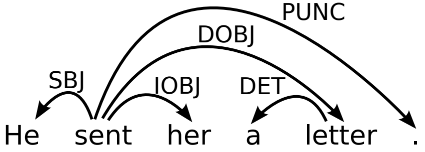
Buffer

[ ]$_B$

Arcs

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

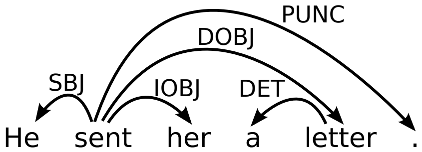
a $\xleftarrow{\text{DET}}$ letter



Non-Optimality

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

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



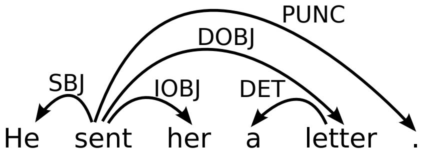
Non-Optimality

Transitions:

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

SH

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

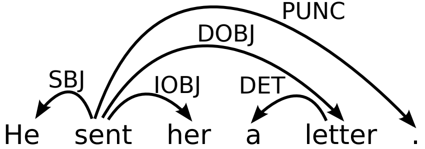


Non-Optimality

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

SH-LA

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



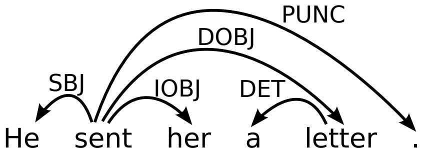
Non-Optimality

Transitions:

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

SH-LA-SH

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

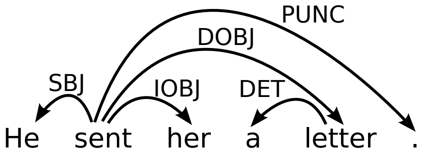


Non-Optimality

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



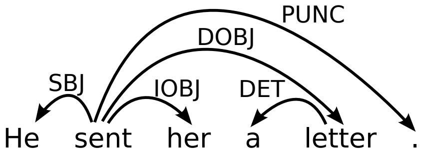
Non-Optimality

Transitions:

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

SH-LA-SH-SH-SH

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



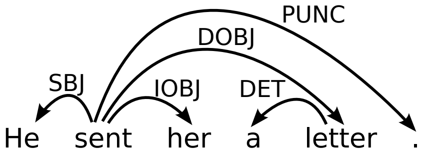
Non-Optimality

Transitions:

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

SH-LA-SH-SH-SH-LA

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



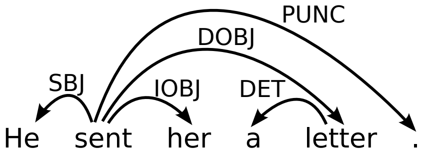
Non-Optimality

Transitions:

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

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

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

$[.]_B$

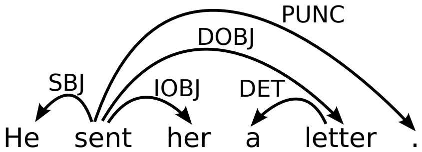
Arcs

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

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

her $\xleftarrow{\text{X}}$ letter

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

$[.]_B$

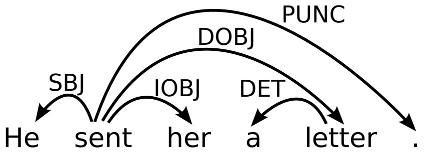
Arcs

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

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

$\text{her} \xleftarrow{\text{X}} \text{letter}$

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



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

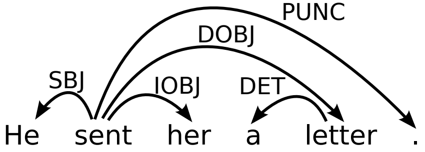
He $\xleftarrow{\text{SBJ}}$ sent

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

her $\xleftarrow{\text{X}}$ letter

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

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



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

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

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

Case by Case

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

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

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

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

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

A New Learning Algorithm

$\textsc{Learn}(\{T_1, \ldots, T_N\})$

$\quad \mathbf{w} \leftarrow 0.0$

$\quad \textbf{for } i \text{ in } 1..K$

$\quad\quad \textbf{for } j \text{ in } 1..N$

$\quad\quad\quad c \leftarrow ([\,]_S, [w_1, \ldots, w_{n_j}]_B, \{\,\})$

$\quad\quad\quad \textbf{while } B_c \neq [\,]$

$\quad\quad\quad\quad t^* \leftarrow \text{argmax}_t\, \mathbf{w} \cdot \mathbf{f}(c, t)$

$\quad\quad\quad\quad t_o \leftarrow \text{argmax}_{t \in \{t | o(c,t,T_i)\}}\, \mathbf{w} \cdot \mathbf{f}(c, t)$

$\quad\quad\quad\quad \textbf{if } t^* \neq t_o$

$\quad\quad\quad\quad\quad \mathbf{w} \leftarrow \mathbf{w} + \mathbf{f}(c, t_o) - \mathbf{f}(c, t^*)$

$\quad\quad\quad\quad c \leftarrow \textsc{choice}(t_o(c), t^*(c))$

$\quad \textbf{return } \mathbf{w}$

A New Learning Algorithm

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

$\mathbf{w} \leftarrow 0.0$

for i in $1..K$

  for j in $1..N$

    $c \leftarrow ([\,]_S, [w_1, \ldots, w_{n_j}]_B, \{\,\})$

    while $B_c \neq [\,]$

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

      $t_o \leftarrow \text{argmax}_{t \in \{t | o(c,t,T_i)\}}\, \mathbf{w} \cdot \mathbf{f}(c, t)$

      if $t^* \neq t_o$

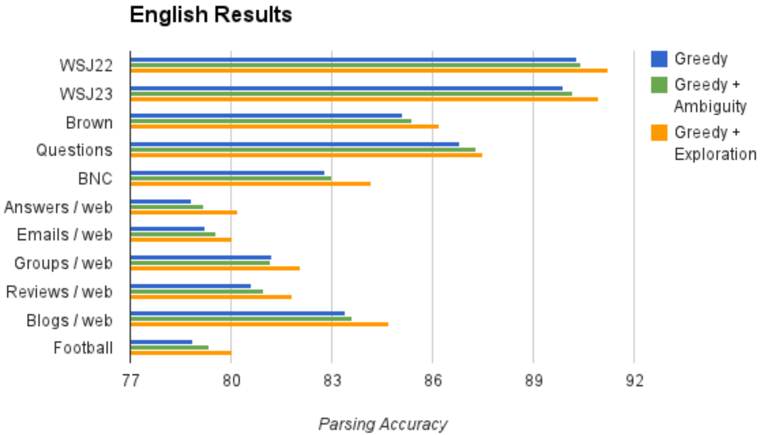
        $\mathbf{w} \leftarrow \mathbf{w} + \mathbf{f}(c, t_o) - \mathbf{f}(c, t^*)$

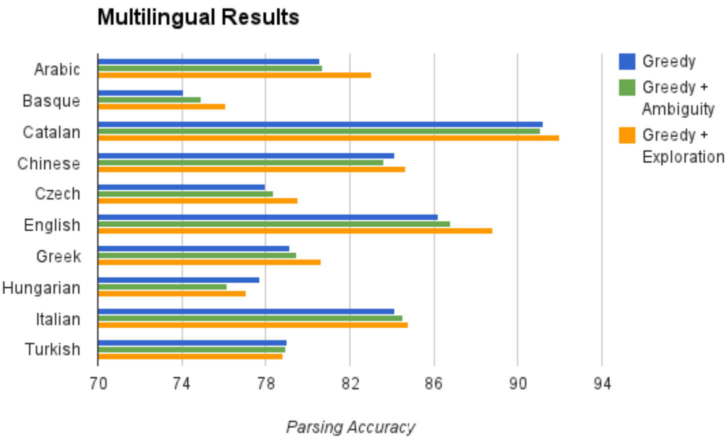
      $c \leftarrow \text{CHOICE}(t_o(c), t^*(c))$

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: $\text{CHOICE}(t_o(c), t^*(c)) = t_o(c)$
  - Greedy + Exploration: Random $\text{CHOICE}(t_o(c), t^*(c))$


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)