



Dependency Parsing

Computational Linguistics: Jordan Boyd-Graber
University of Maryland

EXAMPLES

Processing Shift-Reduce Actions

I am the very model of a modern major general

Processing Shift-Reduce Actions

I am the very model of a modern major general

1. Shift
2. Left
3. Shift
4. Shift
5. Shift

Processing Shift-Reduce Actions

I am the very model of a modern major general

6. Left
7. Left
8. Shift
9. Shift
10. Shift
11. Shift
12. Shift

Processing Shift-Reduce Actions

I am the very model of a modern major general

13. Left
14. Left
15. Left
16. Right
17. Right
18. Right
19. Right
20. Shift

Stack

[root]

Buffer

[I, am, the, very, model, of, a,
modern, major, general]

Edges

Next move: 1. Shift

Stack

[root , I]

Buffer

[am, the, very, model, of, a, modern,
major, general]

Edges

Next move: 2. Left

Stack

[root]

Buffer

[am, the, very, model, of, a, modern,
major, general]

Edges

, l ← am

Next move: 3. Shift

Stack

[root , am]

Buffer

[the, very, model, of, a, modern,
major, general]

Edges

, | ← am

Next move: 4. Shift

Stack

[root , am , the]

Buffer

[very, model, of, a, modern, major,
general]

Edges

, | ← am

Next move: 5. Shift

Stack

[root , am , the , **very**]

Buffer

[model, of, a, modern, major, general]

Edges

, I ← am

Next move: 6. Left

Stack

[root , am , the]

Buffer

[model, of, a, modern, major, general]

Edges

, I ← am

, very ← model

Next move: 7. Left

Stack

[root , am]

Buffer

[model, of, a, modern, major, general]

Edges

, I ← am

, very ← model

, the ← model

Next move: 8. Shift

Stack

[root , am , model]

Buffer

[of, a, modern, major, general]

Edges

, I ← am

, very ← model

, the ← model

Next move: 9. Shift

Stack

[root , am , model , of]

Buffer

[a, modern, major, general]

Edges

, I ← am

, very ← model

, the ← model

Next move: 10. Shift

Stack

[root , am , model , of , a]

Buffer

[modern, major, general]

Edges

, I ← am

, very ← model

, the ← model

Next move: 11. Shift

Stack

[root , am , model , of , a , modern]

Buffer

[major, general]

Edges

, I ← am

, very ← model

, the ← model

Next move: 12. Shift

Stack

[root , am , model , of , a , modern ,
major]

Buffer

[general]

Edges

, I ← am
, very ← model
, the ← model

Next move: 13. Left

Stack

[root , am , model , of , a , modern]

Buffer

[general]

Edges

, I ← am

, very ← model

, the ← model

, major ← general

Next move: 14. Left

Stack

[root , am , model , of , a]

Buffer

[general]

Edges

, I ← am

, very ← model

, the ← model

, major ← general

, modern ← general

Next move: 15. Left

Stack

[root , am , model , of]

Buffer

[general]

Edges

, I ← am

, very ← model

, the ← model

, major ← general

, modern ← general

, a ← general

Next move: 16. Right

Stack

[root , am , model]

Buffer

[of,]

Edges

, I ← am

, very ← model

, the ← model

, major ← general

, modern ← general

, a ← general

, of → general

Next move: 17. Right

Stack

[root , am]

Buffer

[model,]

Edges

, I ← am

, very ← model

, the ← model

, major ← general

, modern ← general

, a ← general

, of → general

, **model** → **of**

Next move: 18. Right

Stack

[root]

Buffer

[am]

Edges

- , I ← am
- , very ← model
- , the ← model
- , major ← general
- , modern ← general
- , a ← general
- , of → general
- , model → of
- , **am → model**

Next move: 19. Right

Stack

[]

Buffer

[root]

Edges

- , I ← am
- , very ← model
- , the ← model
- , major ← general
- , modern ← general
- , a ← general
- , of → general
- , model → of
- , am → model
- , **root → am**

Next move: 20. Shift

Stack

[root]

Buffer

[]

Edges

, I ← am

, very ← model

, the ← model

, major ← general

, modern ← general

, a ← general

, of → general

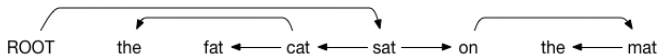
, model → of

, am → model

, root → am

Transition Sequence Algorithm

- Start with root on stack, buffer with whole sentence
- If there's nothing on the stack, you must shift
- If the top of the stack is the child of the top of the buffer, then make a left edge
- If the top of the buffer is is a child of the top of the stack and the top of the buffer has no children that have yet to be added to the tree, then make a right



Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
|--------|------------|-----------|-----------|----------|

s

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |
| I | 4 | sat | 3 | cat |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |
| I | 4 | sat | 3 | cat |
| S | | | | |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |
| I | 4 | sat | 3 | cat |
| S | | | | |
| S | | | | |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |
| I | 4 | sat | 3 | cat |
| S | | | | |
| S | | | | |
| S | | | | |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |
| I | 4 | sat | 3 | cat |
| S | | | | |
| S | | | | |
| S | | | | |
| I | 7 | mat | 6 | the |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |
| I | 4 | sat | 3 | cat |
| S | | | | |
| S | | | | |
| S | | | | |
| I | 7 | mat | 6 | the |
| r | 5 | on | 7 | mat |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| l | 3 | cat | 2 | fat |
| l | 3 | cat | 1 | the |
| S | | | | |
| l | 4 | sat | 3 | cat |
| S | | | | |
| S | | | | |
| S | | | | |
| l | 7 | mat | 6 | the |
| r | 5 | on | 7 | mat |
| r | 4 | sat | 5 | on |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| l | 3 | cat | 2 | fat |
| l | 3 | cat | 1 | the |
| S | | | | |
| l | 4 | sat | 3 | cat |
| S | | | | |
| S | | | | |
| S | | | | |
| l | 7 | mat | 6 | the |
| r | 5 | on | 7 | mat |
| r | 4 | sat | 5 | on |
| r | 0 | None | 4 | sat |

Parse to Transition Sequence

| Action | Head Index | Head Word | Dep Index | Dep Word |
|--------|------------|-----------|-----------|----------|
| S | | | | |
| S | | | | |
| I | 3 | cat | 2 | fat |
| I | 3 | cat | 1 | the |
| S | | | | |
| I | 4 | sat | 3 | cat |
| S | | | | |
| S | | | | |
| S | | | | |
| I | 7 | mat | 6 | the |
| r | 5 | on | 7 | mat |
| r | 4 | sat | 5 | on |
| r | 0 | None | 4 | sat |
| S | | | | |

Eisner Parsing

Given the score function,

$$\lambda = \begin{matrix} & \text{root} & \text{plastic} & \text{cup} & \text{holders} \\ \text{root} & & & & \\ \text{plastic} & & & & \\ \text{cup} & & & & \\ \text{holders} & & & & \end{matrix} \begin{pmatrix} & & & & \\ & 1.0 & 1.0 & 1.0 & \\ -\infty & & -1.0 & -1.0 & \\ -\infty & 2.0 & & -1.0 & \\ -\infty & 0 & 4.0 & & \end{pmatrix}, \quad (1)$$

parse the sentence using the 4-dimensional table presented in the lecture.

Where we use the rules:

1. $C[s][t][\rightarrow][\circ] = \max_{s \leq q < t} C[s][q][\rightarrow][\cdot] + C[q+1][t][\leftarrow][\cdot] + \lambda_{(w_s, w_t)}$
2. $C[s][t][\leftarrow][\circ] = \max_{s \leq q < t} C[s][q][\leftarrow][\cdot] + C[q+1][t][\rightarrow][\cdot] + \lambda_{(w_t, w_s)}$
3. $C[s][t][\rightarrow][\cdot] = \max_{s < q \leq t} C[s][q][\rightarrow][\circ] + C[q][t][\rightarrow][\cdot]$
4. $C[s][t][\leftarrow][\cdot] = \max_{s \leq q < t} C[s][q][\leftarrow][\cdot] + C[q][t][\leftarrow][\circ]$

to complete a 4-chart with entries for spans that start at s , end at t , and are either right \rightarrow or left \leftarrow directed and either incomplete \circ or complete \cdot .

Span 1,2

1. $C[1,2, \leftarrow, \circ] =$

2. $C[1,2, \rightarrow, \circ] =$

3. $C[1,2, \leftarrow, \cdot] =$

4. $C[1,2, \rightarrow, \cdot] =$

Span 1,2

1. $C[1,2,\leftarrow,\circ] = C[1,1,\rightarrow,\cdot] + C[2,2,\leftarrow,\cdot] + \lambda_{2,1} = \lambda_{2,1} = -\infty$

2. $C[1,2,\rightarrow,\circ] =$

3. $C[1,2,\leftarrow,\cdot] =$

4. $C[1,2,\rightarrow,\cdot] =$

Span 1,2

1. $C[1,2,\leftarrow,\circ] = C[1,1,\rightarrow,\cdot] + C[2,2,\leftarrow,\cdot] + \lambda_{2,1} = \lambda_{2,1} = -\infty$

2. $C[1,2,\rightarrow,\circ] = C[1,1,\rightarrow,\cdot] + C[2,2,\leftarrow,\cdot] + \lambda_{1,2} = 1$

3. $C[1,2,\leftarrow,\cdot] =$

4. $C[1,2,\rightarrow,\cdot] =$

Span 1,2

1. $C[1,2,\leftarrow,\circ] = C[1,1,\rightarrow,\cdot] + C[2,2,\leftarrow,\cdot] + \lambda_{2,1} = \lambda_{2,1} = -\infty$

2. $C[1,2,\rightarrow,\circ] = C[1,1,\rightarrow,\cdot] + C[2,2,\leftarrow,\cdot] + \lambda_{1,2} = 1$

3. $C[1,2,\leftarrow,\cdot] = C[1,1,\leftarrow,\cdot] + C[1,2,\leftarrow,\circ] = C[1,2,\leftarrow,\circ] = \lambda_{2,1} = -\infty$

4. $C[1,2,\rightarrow,\cdot] =$

Span 1,2

1. $C[1,2,\leftarrow,\circ] = C[1,1,\rightarrow,\cdot] + C[2,2,\leftarrow,\cdot] + \lambda_{2,1} = \lambda_{2,1} = -\infty$
2. $C[1,2,\rightarrow,\circ] = C[1,1,\rightarrow,\cdot] + C[2,2,\leftarrow,\cdot] + \lambda_{1,2} = 1$
3. $C[1,2,\leftarrow,\cdot] = C[1,1,\leftarrow,\cdot] + C[1,2,\leftarrow,\circ] = C[1,2,\leftarrow,\circ] = \lambda_{2,1} = -\infty$
4. $C[1,2,\rightarrow,\cdot] = C[1,2,\rightarrow,\circ] + C[2,2,\rightarrow,\cdot] = C[1,2,\rightarrow,\circ] = \lambda_{1,2} = 1$

Span 2,3

1. $C[2,3, \leftarrow, \circ] =$

2. $C[2,3, \rightarrow, \circ] =$

3. $C[2,3, \leftarrow, \cdot] =$

4. $C[2,3, \rightarrow, \cdot] =$

Span 2,3

1. $C[2,3, \leftarrow, \circ] = \lambda_{3,2} = 2$

2. $C[2,3, \rightarrow, \circ] =$

3. $C[2,3, \leftarrow, \cdot] =$

4. $C[2,3, \rightarrow, \cdot] =$

Span 2,3

1. $C[2,3,\leftarrow,\circ] = \lambda_{3,2} = 2$

2. $C[2,3,\rightarrow,\circ] = \lambda_{2,3} = -1$

3. $C[2,3,\leftarrow,\cdot] =$

4. $C[2,3,\rightarrow,\cdot] =$

Span 2,3

1. $C[2,3,\leftarrow,\circ] = \lambda_{3,2} = 2$

2. $C[2,3,\rightarrow,\circ] = \lambda_{2,3} = -1$

3. $C[2,3,\leftarrow,\cdot] = C[2,3,\leftarrow,\circ] = 2$

4. $C[2,3,\rightarrow,\cdot] =$

Span 2,3

1. $C[2,3,\leftarrow,\circ] = \lambda_{3,2} = 2$

2. $C[2,3,\rightarrow,\circ] = \lambda_{2,3} = -1$

3. $C[2,3,\leftarrow,\cdot] = C[2,3,\leftarrow,\circ] = 2$

4. $C[2,3,\rightarrow,\cdot] = C[2,3,\rightarrow,\circ] = -1$

Span 3,4

1. $C[3,4,\leftarrow,\circ] = \lambda_{4,3} = 4$

2. $C[3,4,\rightarrow,\circ] = \lambda_{3,4} = -1$

3. $C[3,4,\leftarrow,\cdot] = C[3,4,\leftarrow,\circ] = 4$

4. $C[3,4,\rightarrow,\cdot] = C[3,4,\rightarrow,\circ] = -1$

Span 1,3

1.

$$\begin{aligned} C[1,3,\leftarrow,\circ] &= \max(C[1,1,\rightarrow,\cdot] + C[2,3,\leftarrow,\cdot], \\ &\quad C[1,2,\rightarrow,\cdot] + C[3,3,\leftarrow,\cdot]) + \lambda_{3,1} \\ &= \lambda_{3,1} + \lambda_{3,2} = -\infty \end{aligned}$$

Span 1,3

1.

$$C[1, 3, \leftarrow, \circ] = -\infty$$

Span 1,3

1.

$$C[1,3,\leftarrow,\circ] = -\infty$$

2.

$$\begin{aligned} C[1,3,\rightarrow,\circ] &= \max(C[2,3,\leftarrow,\cdot], C[1,2,\rightarrow,\cdot]) + \lambda_{1,3} \\ &= \lambda_{3,2} + \lambda_{1,3} = 3 \end{aligned}$$

Span 1,3

1.

$$C[1, 3, \leftarrow, \circ] = -\infty$$

2.

$$C[1, 3, \rightarrow, \circ] = 3$$

Span 1,3

1.

$$C[1,3,\leftarrow,\circ] = -\infty$$

2.

$$C[1,3,\rightarrow,\circ] = 3$$

3.

$$\begin{aligned} C[1,3,\leftarrow,\cdot] &= \max(C[1,1,\leftarrow,\cdot] + C[1,3,\leftarrow,\circ], C[1,2,\leftarrow,\cdot] + C[2,3,\rightarrow,\circ]) \\ &= \max(0 - \infty, -\infty + 2) = -\infty \end{aligned}$$

Span 1,3

1.

$$C[1,3,\leftarrow,\circ] = -\infty$$

2.

$$C[1,3,\rightarrow,\circ] = 3$$

3.

$$C[1,3,\leftarrow,\cdot] = -\infty$$

4.

$$\begin{aligned} C[1,3,\rightarrow,\cdot] &= \max(C[1,2,\rightarrow,\circ] + C[2,3,\rightarrow,\cdot], \\ &\quad \underline{C[1,3,\rightarrow,\circ] + C[3,3,\rightarrow,\cdot]}) \\ &= \max(\lambda_{1,2} + \lambda_{2,3}, \underline{\lambda_{1,3} + \lambda_{3,2}}) = \max(0, \underline{3}) = 3 \end{aligned}$$

Span 2,4

1.

$$\begin{aligned}C[2, 4, \leftarrow, \circ] &= \max(C[2, 2, \rightarrow, \cdot] + C[3, 4, \leftarrow, \cdot], \\ &\quad C[2, 3, \rightarrow, \cdot] + C[4, 4, \leftarrow, \cdot]) + \lambda_{4,2} \\ &= \max(\underline{C[3, 4, \leftarrow, \cdot]}, C[2, 3, \rightarrow, \cdot]) + \lambda_{4,2} \\ &= \max(\underline{\lambda_{4,3}}, \lambda_{2,3}) + \lambda_{4,2} = 4 + 0 = 4\end{aligned}$$

Span 2,4

1.

$$C[2, 4, \leftarrow, \circ] = \max(\lambda_{4,3}, \lambda_{2,3}) + \lambda_{4,2} = 4 + 0 = 4$$

2.

$$\begin{aligned} C[2, 4, \rightarrow, \circ] &= \max(C[2, 2, \rightarrow, \cdot] + C[3, 4, \leftarrow, \cdot], \\ &\quad C[2, 3, \rightarrow, \cdot] + C[4, 4, \leftarrow, \cdot]) + \lambda_{2,4} \\ &= \max(\lambda_{4,3}, \lambda_{2,3}) + \lambda_{2,4} = 3 \end{aligned}$$

Span 2,4

1.

$$C[2, 4, \leftarrow, \circ] = \max(\lambda_{4,3}, \lambda_{2,3}) + \lambda_{4,2} = 4 + 0 = 4$$

2.

$$C[2, 4, \rightarrow, \circ] = 3$$

3.

$$\begin{aligned} C[2, 4, \leftarrow, \cdot] &= \max(C[2, 4, \rightarrow, \circ], C[2, 3, \leftarrow, \cdot] + C[3, 4, \leftarrow, \circ]) \\ &= \max(\lambda_{4,2} + \lambda_{4,3}, \\ &\quad \underline{\lambda_{3,2} + \lambda_{4,3}}) = 6 \end{aligned}$$

Span 2,4

1.

$$C[2, 4, \leftarrow, \circ] = \max(\lambda_{4,3}, \lambda_{2,3}) + \lambda_{4,2} = 4 + 0 = 4$$

2.

$$C[2, 4, \rightarrow, \circ] = 3$$

3.

$$C[2, 4, \leftarrow, \cdot] = 6$$

4.

$$C[2, 4, \rightarrow, \cdot] = \max(C[2, 3, \rightarrow, \circ] + C[3, 4, \rightarrow, \cdot], C[2, 4, \rightarrow, \circ]) = \max(\lambda_{2,3} + \lambda_{3,4}, \lambda_{2,4} + \lambda_{4,3}) = 3$$

Span 1,4

1.

$$C[1,4,\leftarrow,\circ] = \lambda_{4,1} + \dots = -\infty$$

Span 1,4

1.

$$C[1,4,\leftarrow,\circ] = \lambda_{4,1} + \dots = -\infty$$

2.

$$\begin{aligned} C[1,4,\rightarrow,\circ] &= \max(C[2,4,\leftarrow,\cdot], \\ &\quad C[1,2,\rightarrow,\cdot] + C[3,4,\leftarrow,\cdot], \\ &\quad C[1,3,\rightarrow,\cdot]) + \lambda_{1,4} \\ &= \max(\lambda_{3,2} + \lambda_{4,3}, \underline{\lambda_{1,2} + \lambda_{4,3}}, \lambda_{1,2} + \lambda_{4,3}, \lambda_{1,3} + \lambda_{3,2}) \\ &= 6 + 1 = 7 \end{aligned}$$

Span 1,4

1.

$$C[1,4,\leftarrow,\circ] = \lambda_{4,1} + \dots = -\infty$$

2.

$$C[1,4,\rightarrow,\circ] = 7$$

3. $C[1,4,\leftarrow,\cdot] = \max(0 + -\infty, -\infty + \dots, -\infty + \dots) = -\infty$

Span 1,4

1.

$$C[1,4,\leftarrow,\circ] = \lambda_{4,1} + \dots = -\infty$$

2.

$$C[1,4,\rightarrow,\circ] = 7$$

3. $C[1,4,\leftarrow,\cdot] = \max(0 + -\infty, -\infty + \dots, -\infty + \dots) = -\infty$

4.

$$\begin{aligned} C[1,4,\rightarrow,\cdot] &= \max(C[1,2,\rightarrow,\circ] + C[2,4,\rightarrow,\cdot], \\ &\quad C[1,3,\rightarrow,\circ] + C[3,4,\rightarrow,\cdot], \\ &\quad C[1,4,\rightarrow,\circ]) \\ &= \max(\lambda_{1,2} + \lambda_{2,4} + \lambda_{4,3} + \lambda_{1,3} + \lambda_{3,2} + \lambda_{3,4}, \\ &\quad \underline{\lambda_{1,4} + \lambda_{4,3} + \lambda_{3,2}}) \\ &= \max(1 + 3, 3 - 1, \underline{1 + 4 + 2}) = 7 \end{aligned}$$

Reconstruction

