COMP 4446 / 5046
Lecture 5: Inference – Dynamic Programming

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Semester 1, 2025

THE UNIVERSITY OF SYDNEY

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Language Nerd

[Not to go all sentence fragment on you.]

Source: https://xkcd.com/1443/

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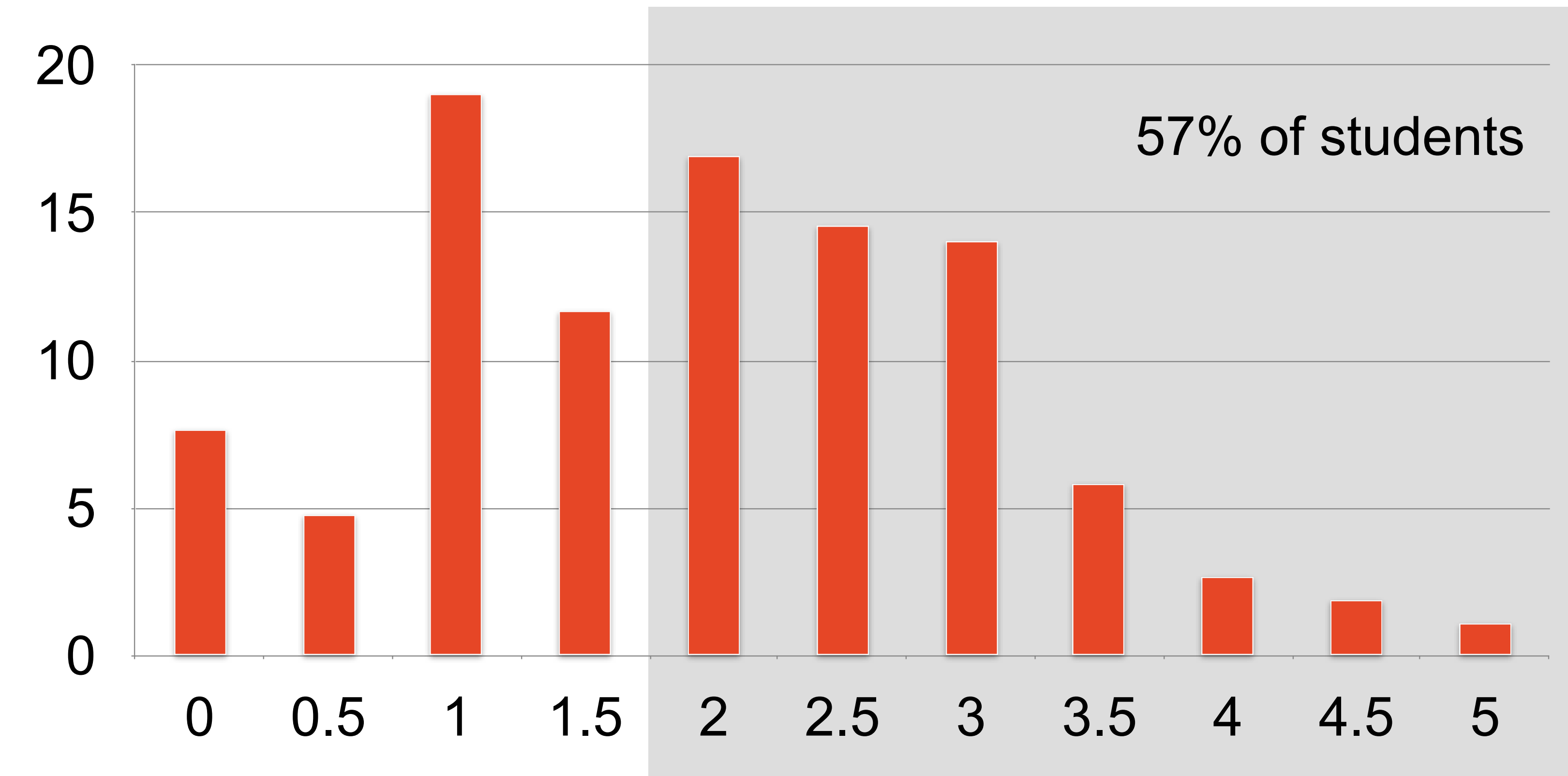
The quiz was representative of the exam and 43% of students scored under 2. What next?



Me: Working to give more support

You: Engage with all components of the unit

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Sequence Tagging

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We will consider various sequences and tags

way 1

B-PER	O	O
Joe	likes	trucks

2

Noun	Verb	Noun
Joe	likes	trucks

input

Sequences are a fixed, known, length
Tags are from a small-ish, fixed, set

should be small, otherwise, computational cost ↑

Independent predictions can be inconsistent

Possible independent predictions:

2 mistake

B-ORG	I-ORG	O	B-LOC	O	O	O	···

True labels:

B-ORG	I-ORG	I-ORG	I-ORG	O	O	O	···
The	University	of	Sydney	is	located	in	…

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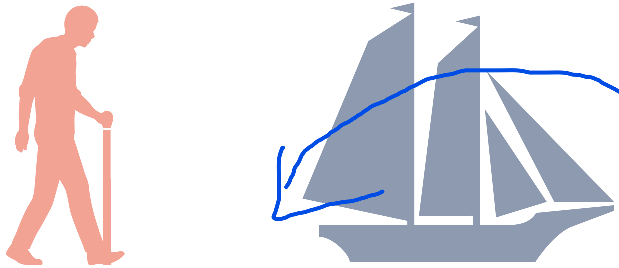
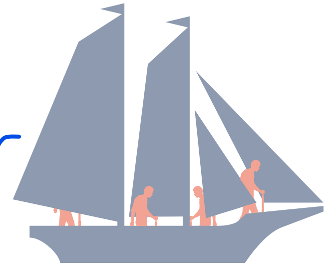
Greedy predictions can make mistakes that become clear too late



Predictions:	Det	Adj.	Noun	Det	Noun

Error



True labels:	Det	Noun	Verb	Det	Noun
	The	old	man	the	boat

A greedy method can't go back and undo the choices Adj & Noun!

"The old man" originally good goes bad latter

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Considering each tag sequence separately is not feasible

17 tags in Universal Dependencies

$\text{Options} = |\text{tags}|^{|\text{words}|}$

For the last example,

17^5 = 1,419,857 options

For a 20 word sentence (average length in news):

17^{20} = 4,064,231,406,647,572,522,401,601
(4.1 Septillion)

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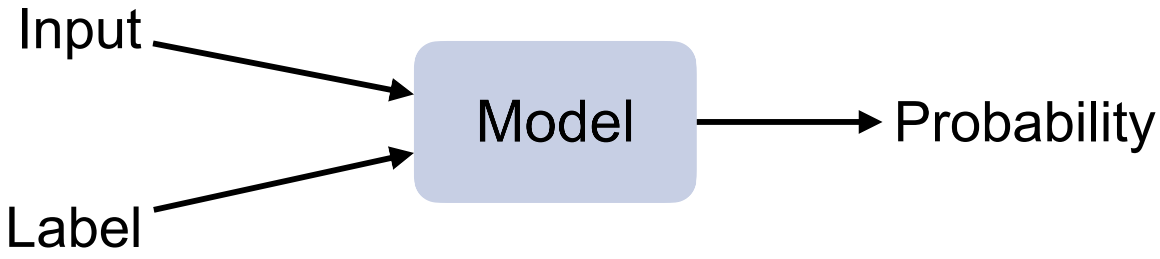
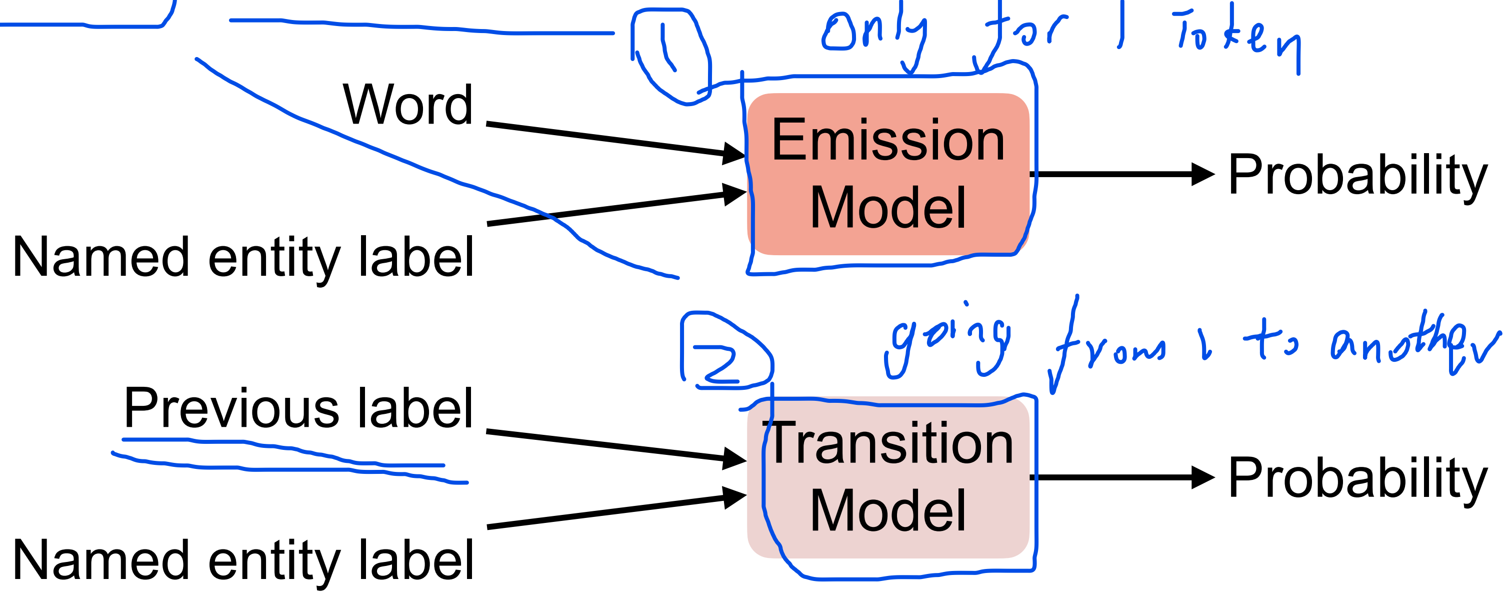
For certain models we can find the highest scoring sequence efficiently



new

Our model needs to calculate the score in pieces of two types:



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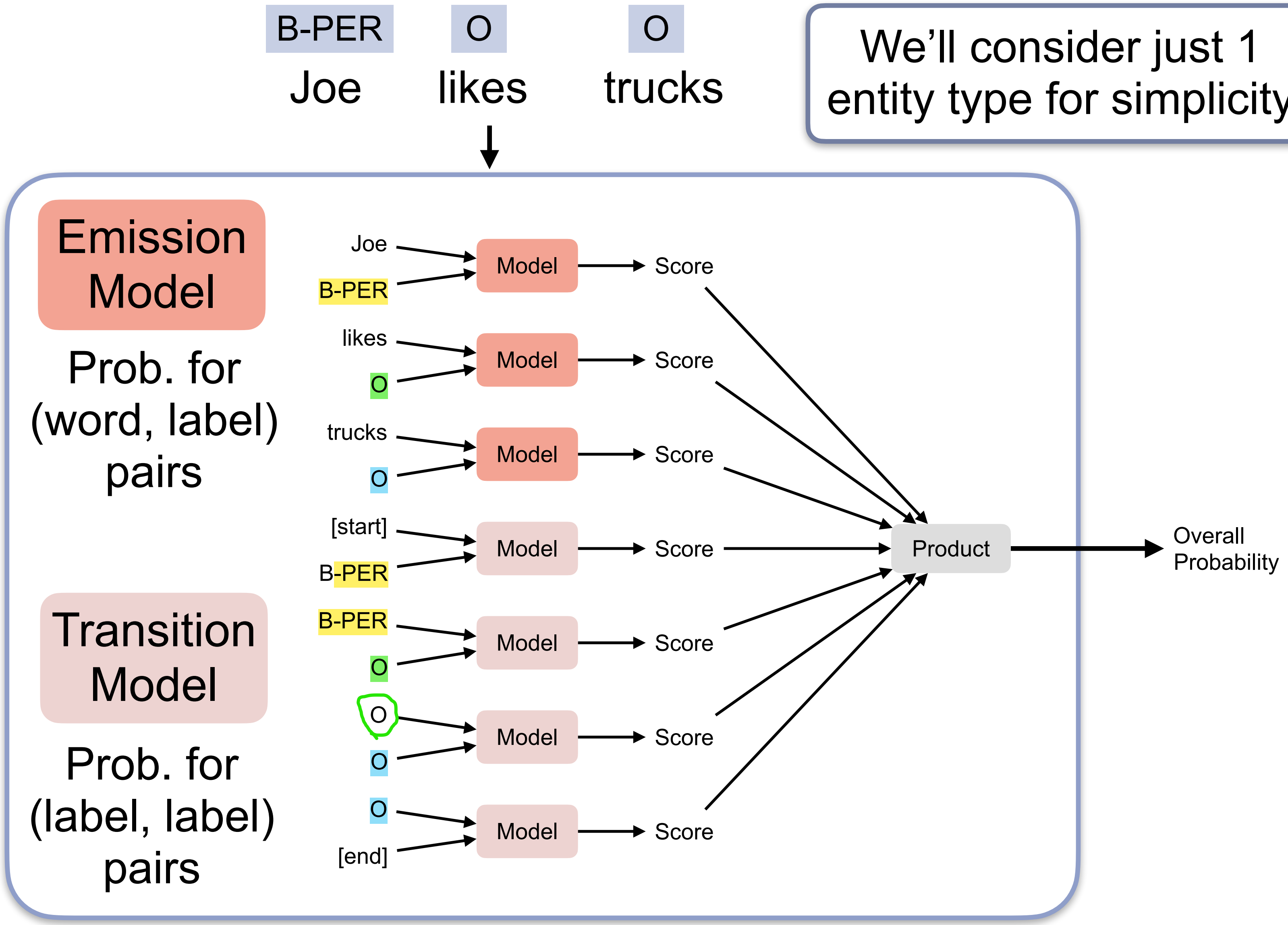
We can still think of it as a model for whole sequences

We'll consider just 1 entity type for simplicity



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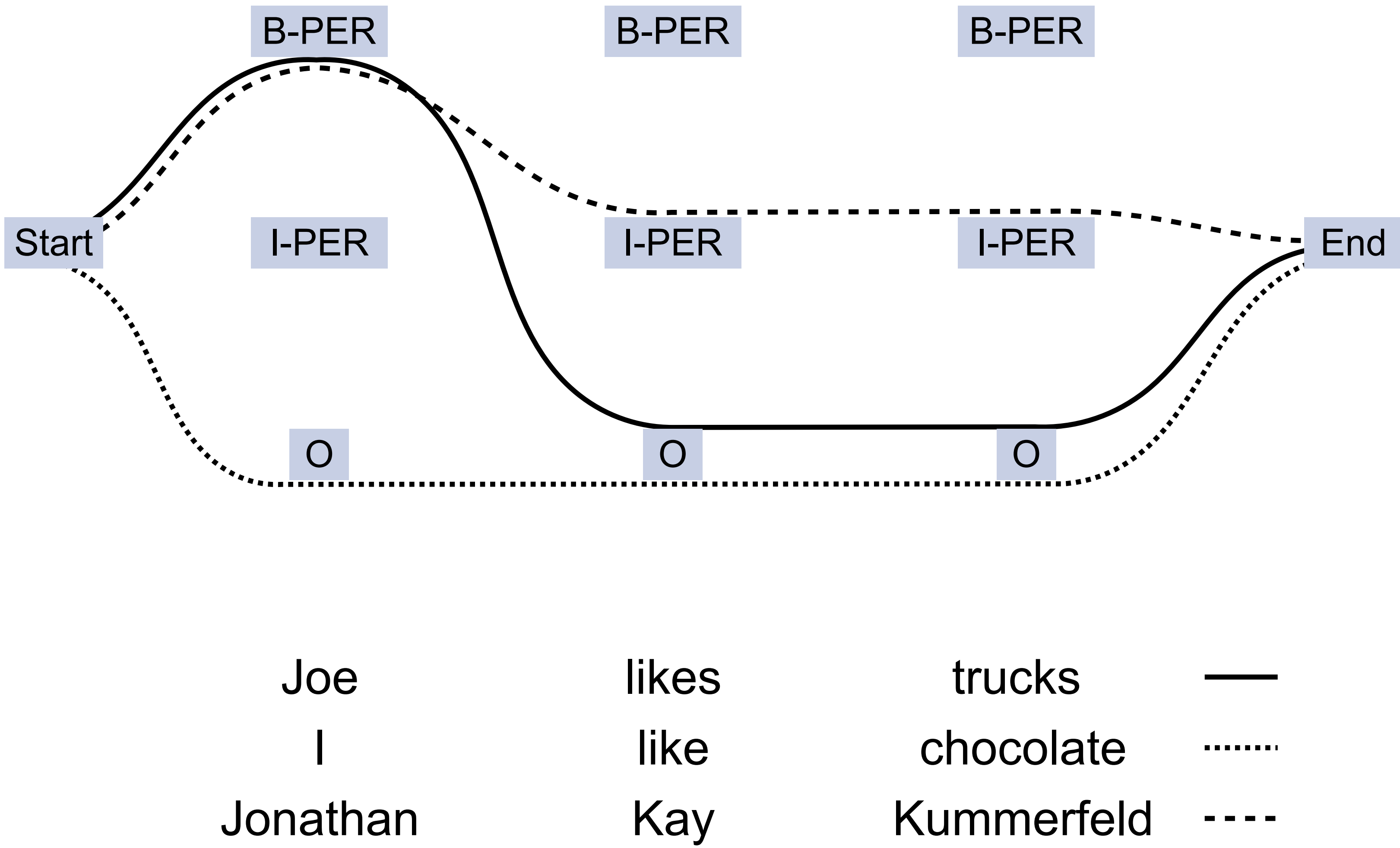
To understand the algorithm, we can draw paths through a grid of labels



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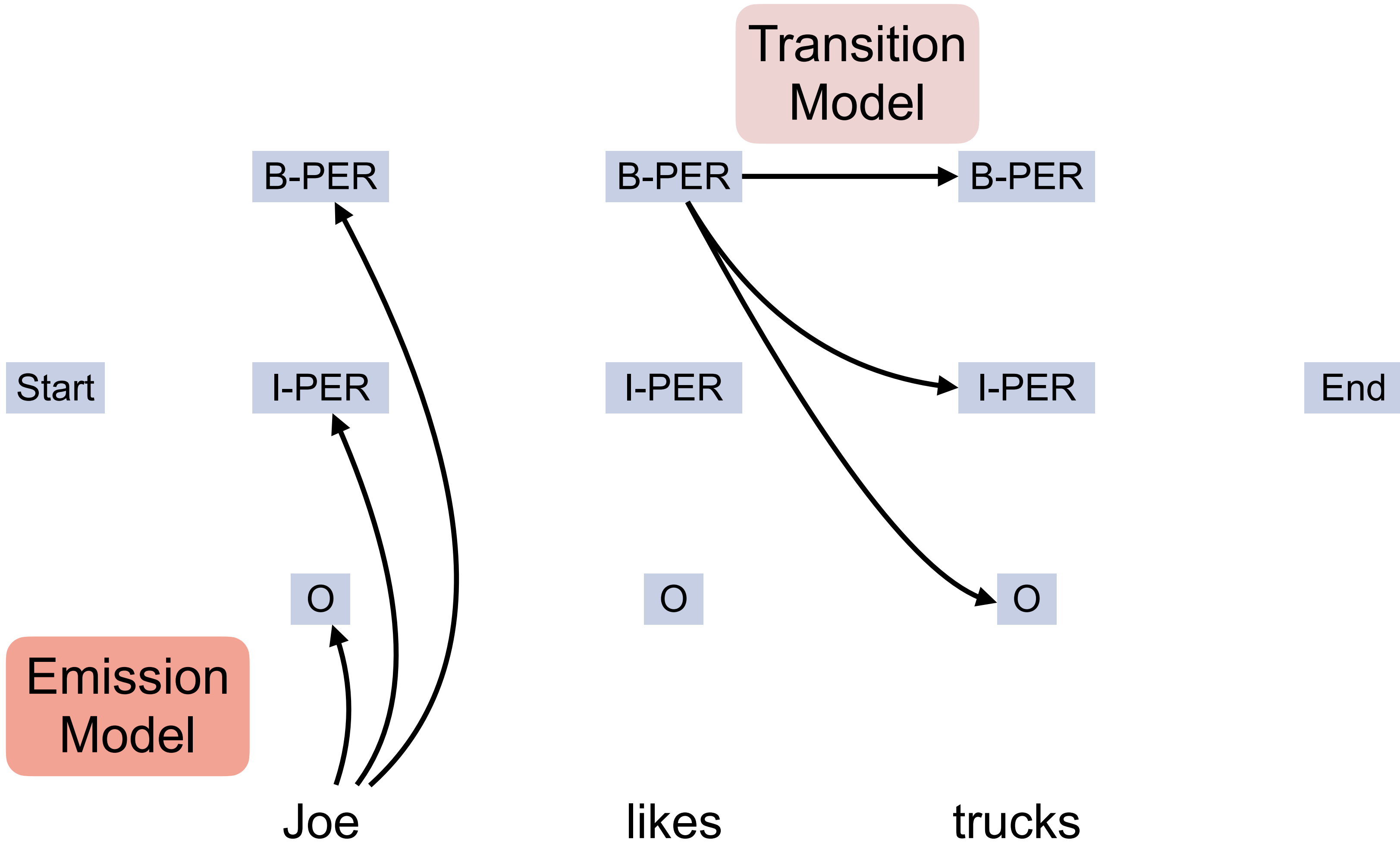
The two model parts from earlier correspond to parts of this grid



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You can read it as output of transition model

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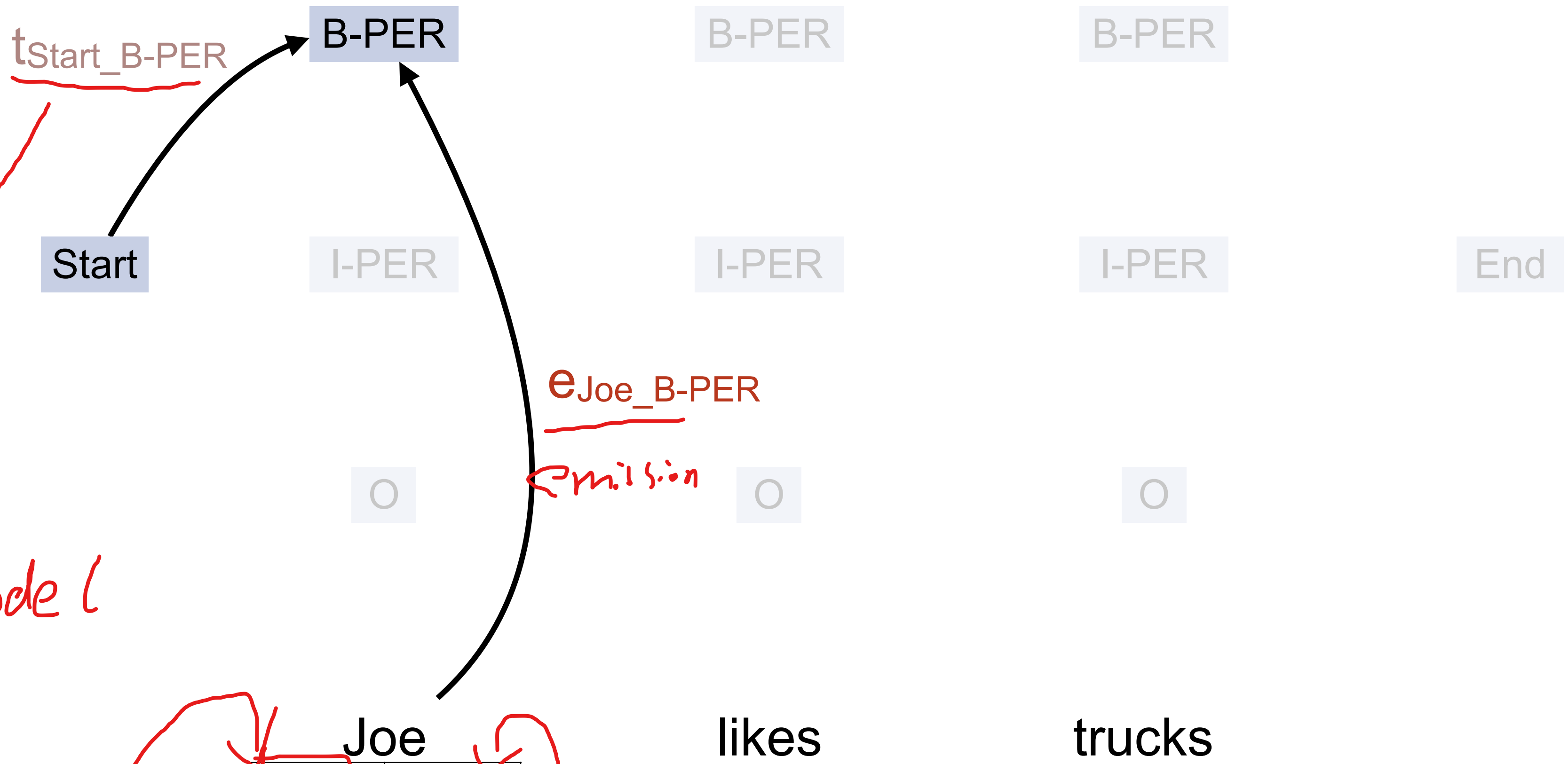
We calculate intermediate scores, first for each possible start

emission transition

$$\boxed{prob_1} = e_{Joe\_B\text{-}PER} * t_{Start\_B\text{-}PER}$$

transition



Prob.

$prob_1$	Start

Previous state

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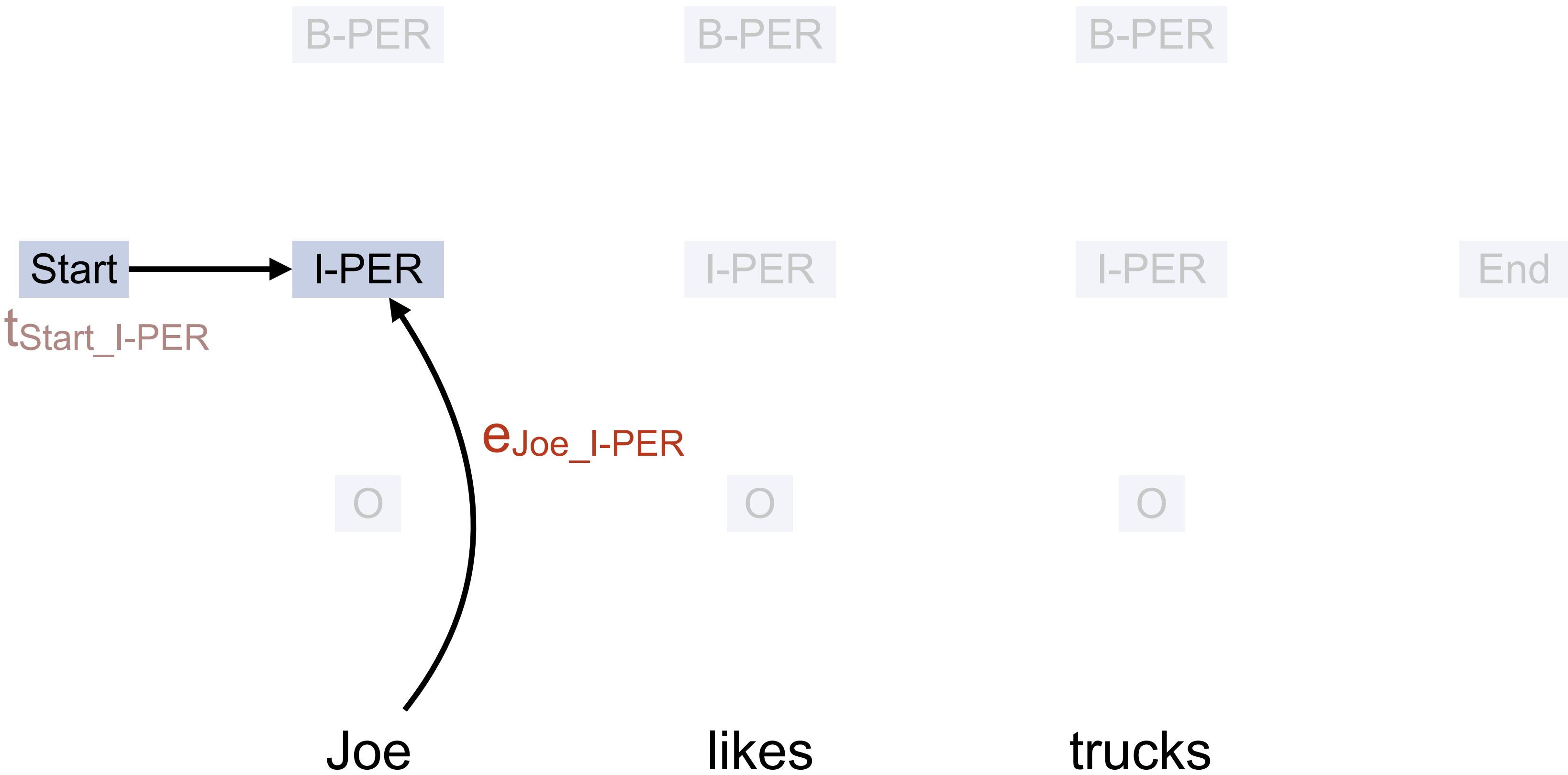
We calculate intermediate scores, first for each possible start

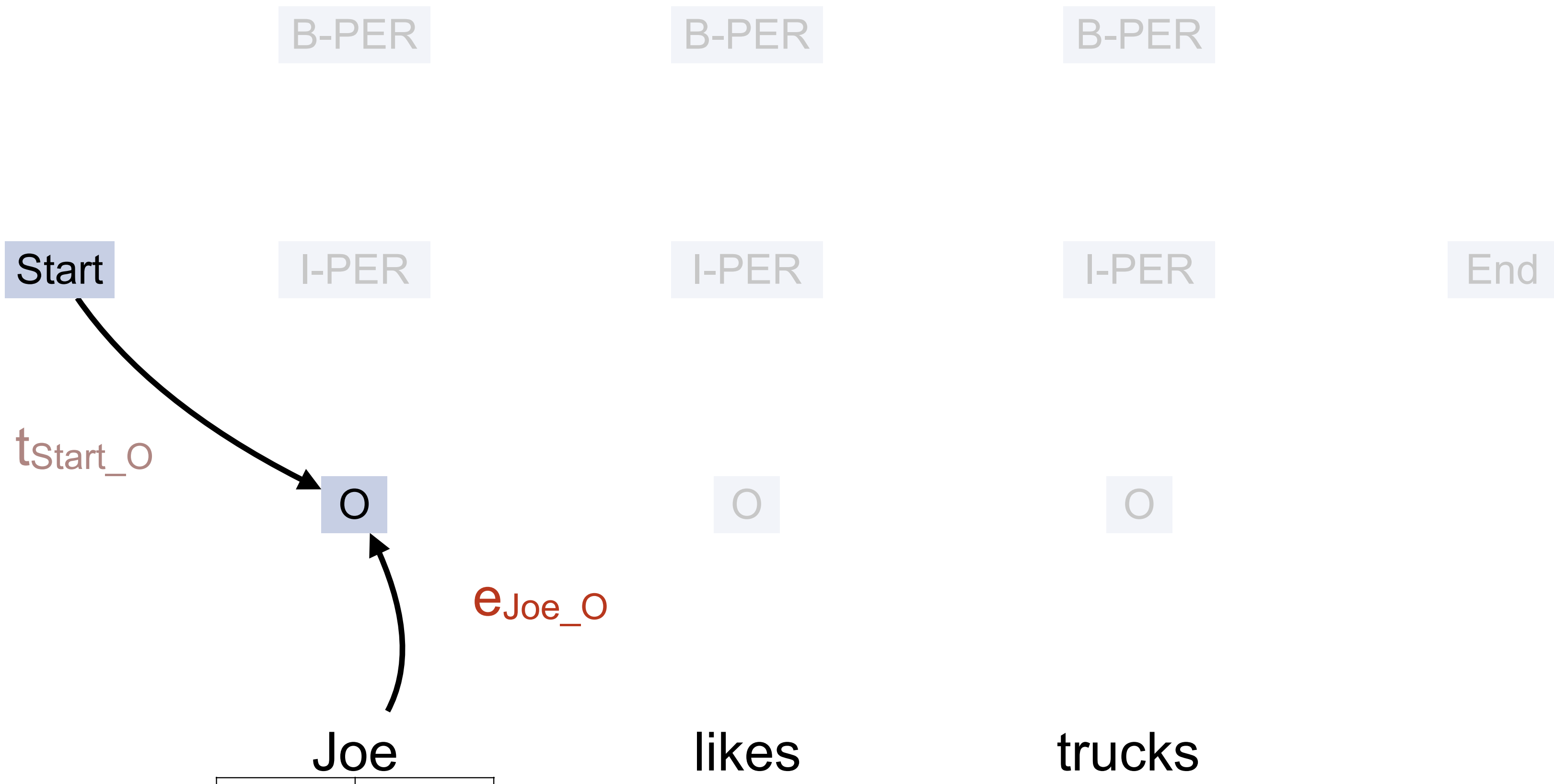
$$prob_2 = e_{Joe\_I\text{-}PER} * t_{Start\_I\text{-}PER}$$



$prob_1$	Start
$prob_2$	Start

We calculate intermediate scores, first for each possible start

$$prob_3 = e_{Joe\_O} * t_{Start\_O}$$



$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

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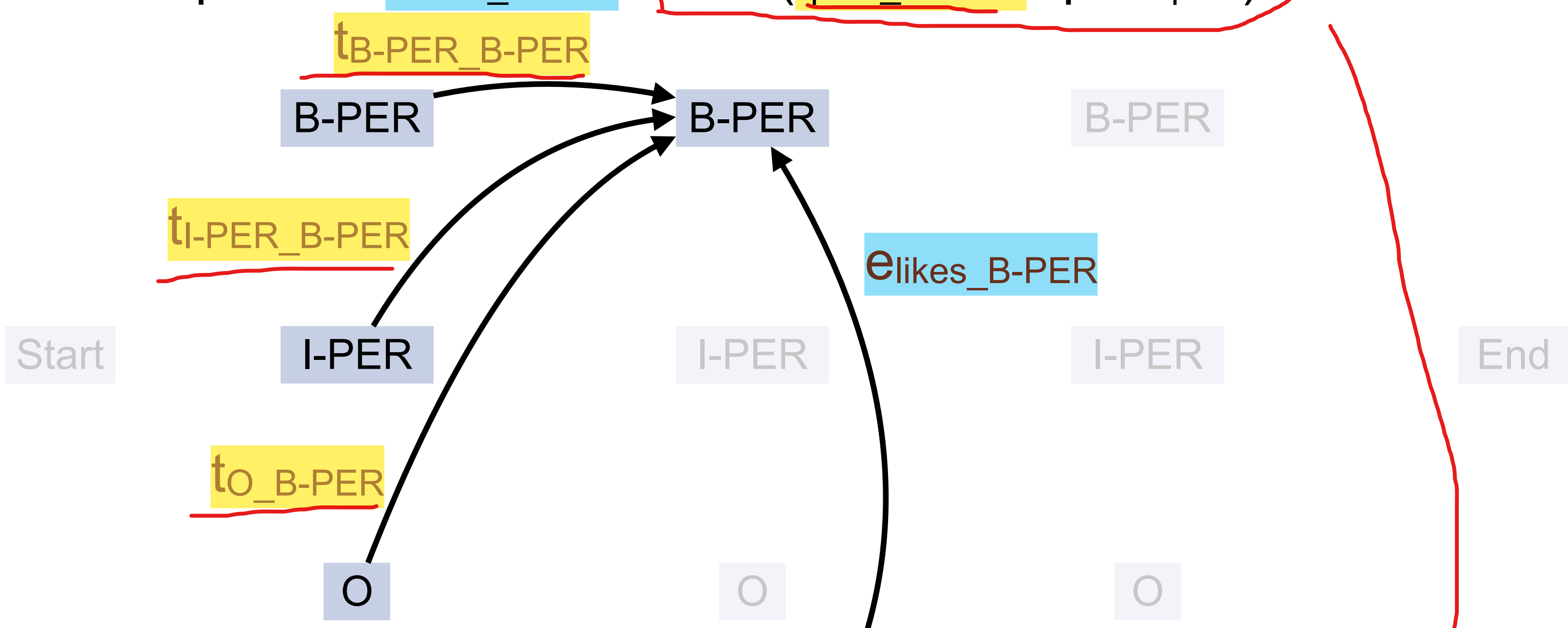
We calculate intermediate scores, then continuations, noting the best

$$prob_4 = e_{likes\_B\text{-}PER} * \max(t_{prev\_B\text{-}PER} * prob_{prev})$$



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	

trucks

Example

O, B-PER is max

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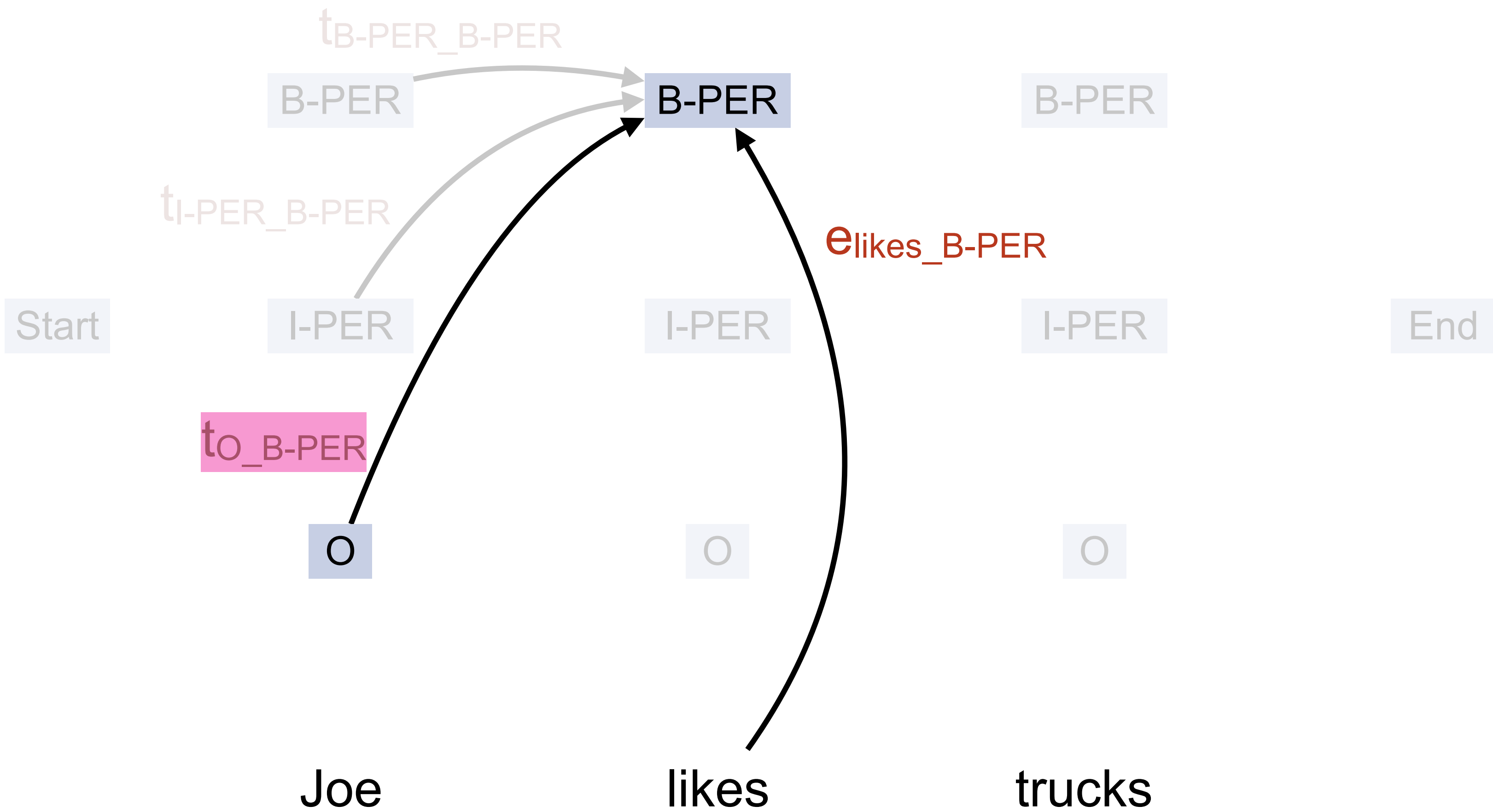
We calculate intermediate scores, then continuations, noting the best

$$prob_4 = e_{likes\_B\text{-}PER} * \max(t_{prev\_B\text{-}PER} * prob_{prev})$$



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O

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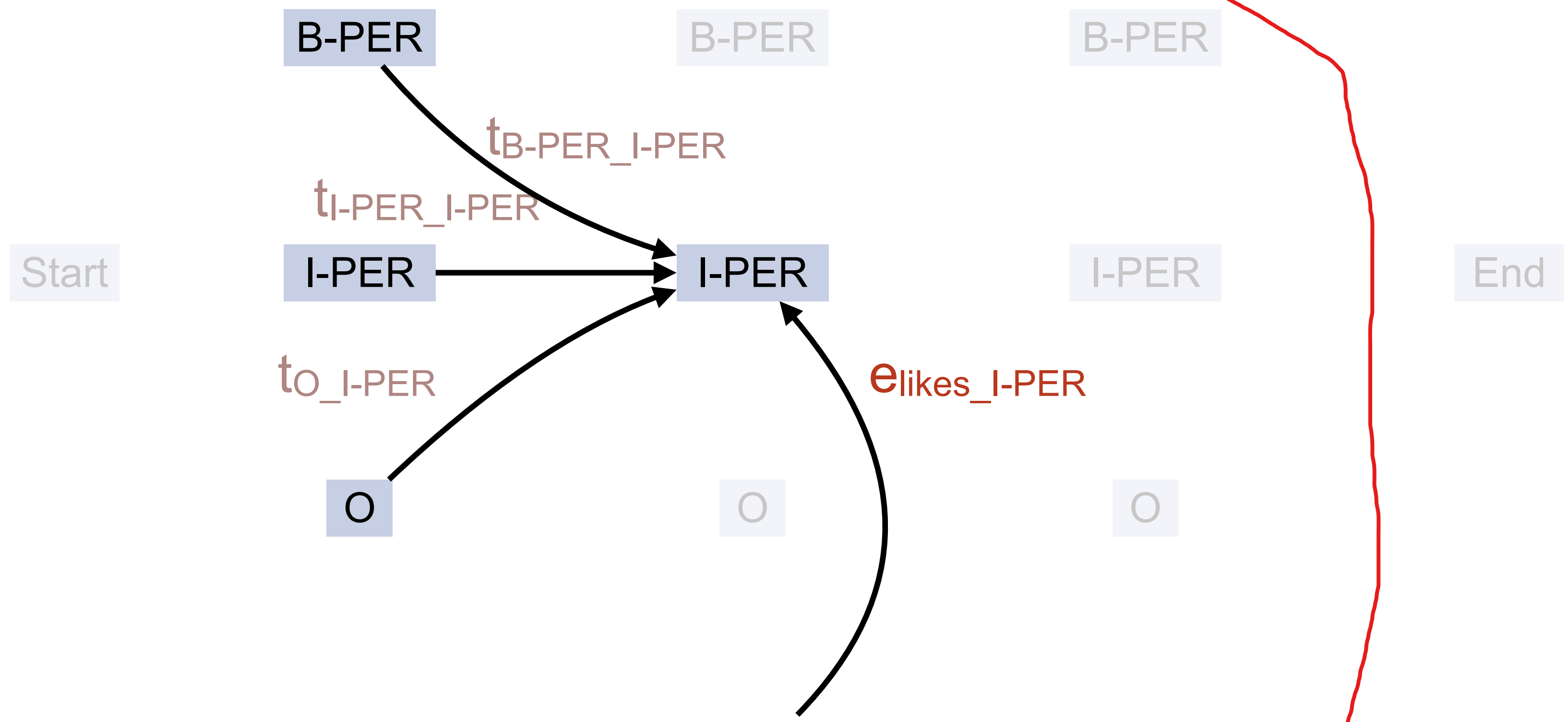
We calculate intermediate scores, then continuations, noting the best

$$\text{prob}_5 = e_{\text{likes\_I-PER}} * \max(t_{\text{prev\_I-PER}} * \text{prob}_{\text{prev}})$$



Joe

prob_1	Start
prob_2	Start
prob_3	Start

likes

prob_4	O
prob_5	

trucks

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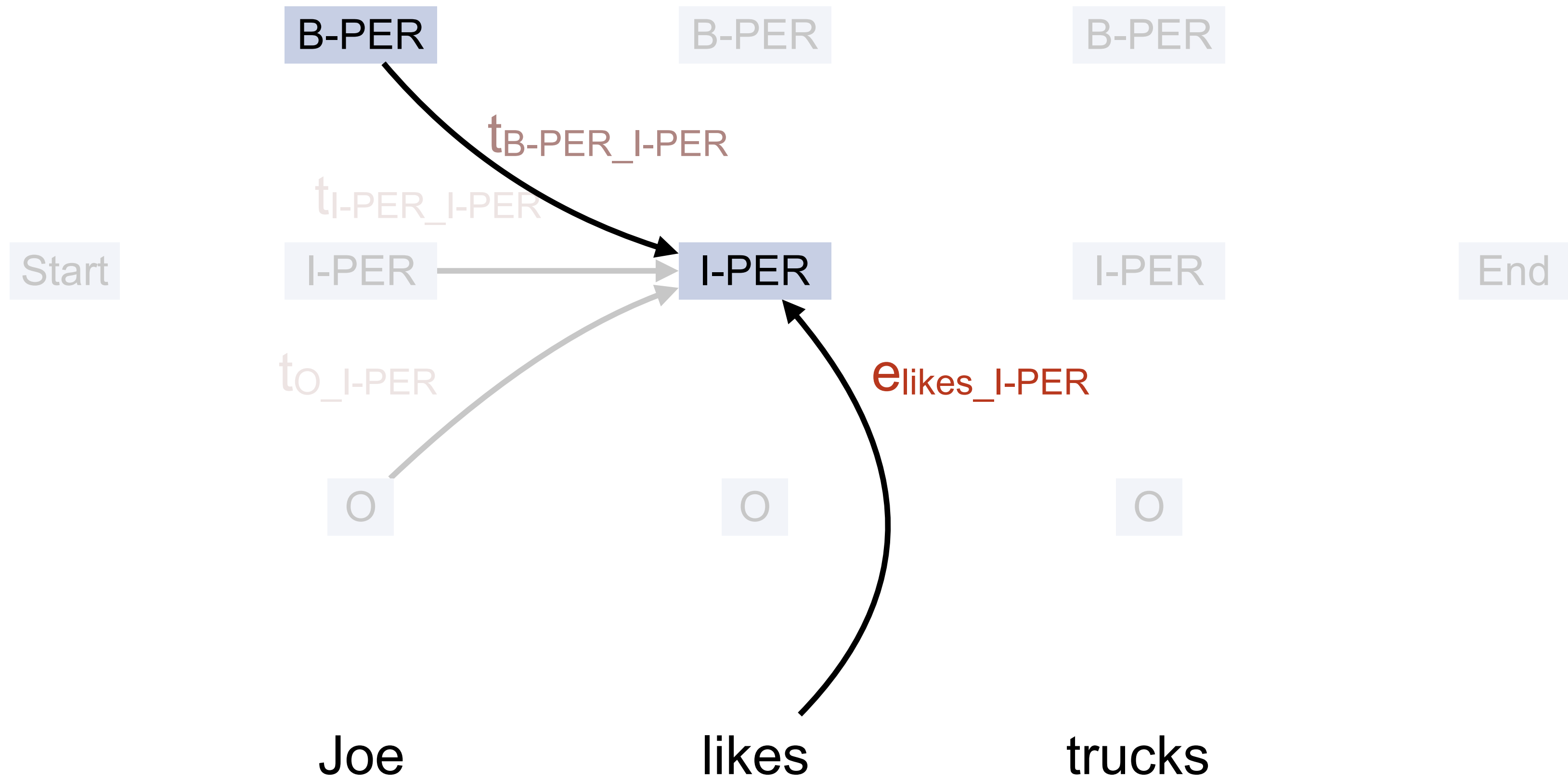
We calculate intermediate scores, then continuations, noting the best

$$prob_5 = e_{likes\_I\text{-}PER} * \max(t_{prev\_I\text{-}PER} * prob_{prev})$$



$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

$prob_4$	O
$prob_5$	B-PER

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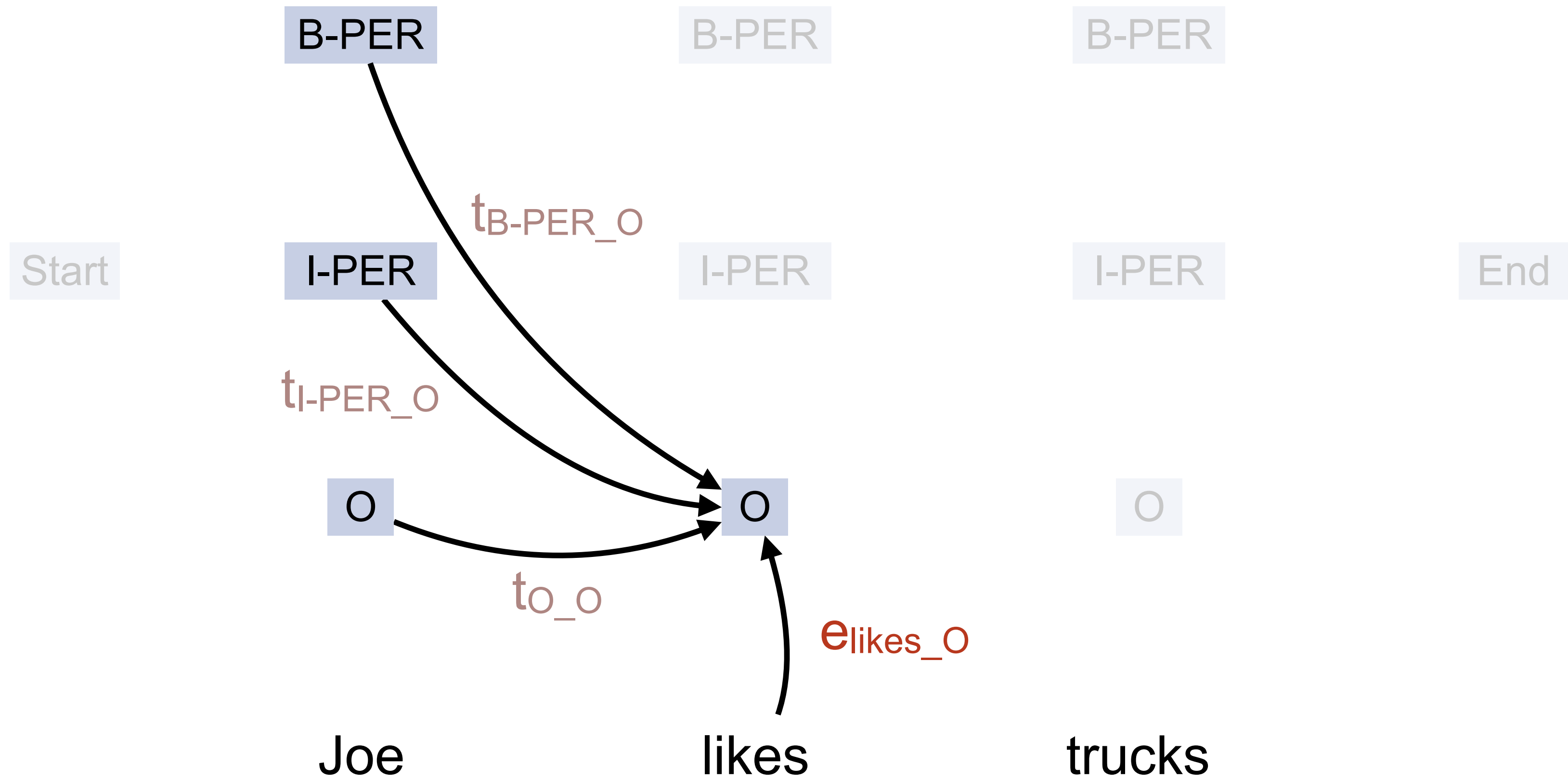
We calculate intermediate scores, then continuations, noting the best

$$\text{prob}_6 = e_{\text{likes\_O}} * \max(t_{\text{prev\_O}} * \text{prob}_{\text{prev}})$$



prob_1	Start
prob_2	Start
prob_3	Start

prob_4	O
prob_5	B-PER
prob_6	

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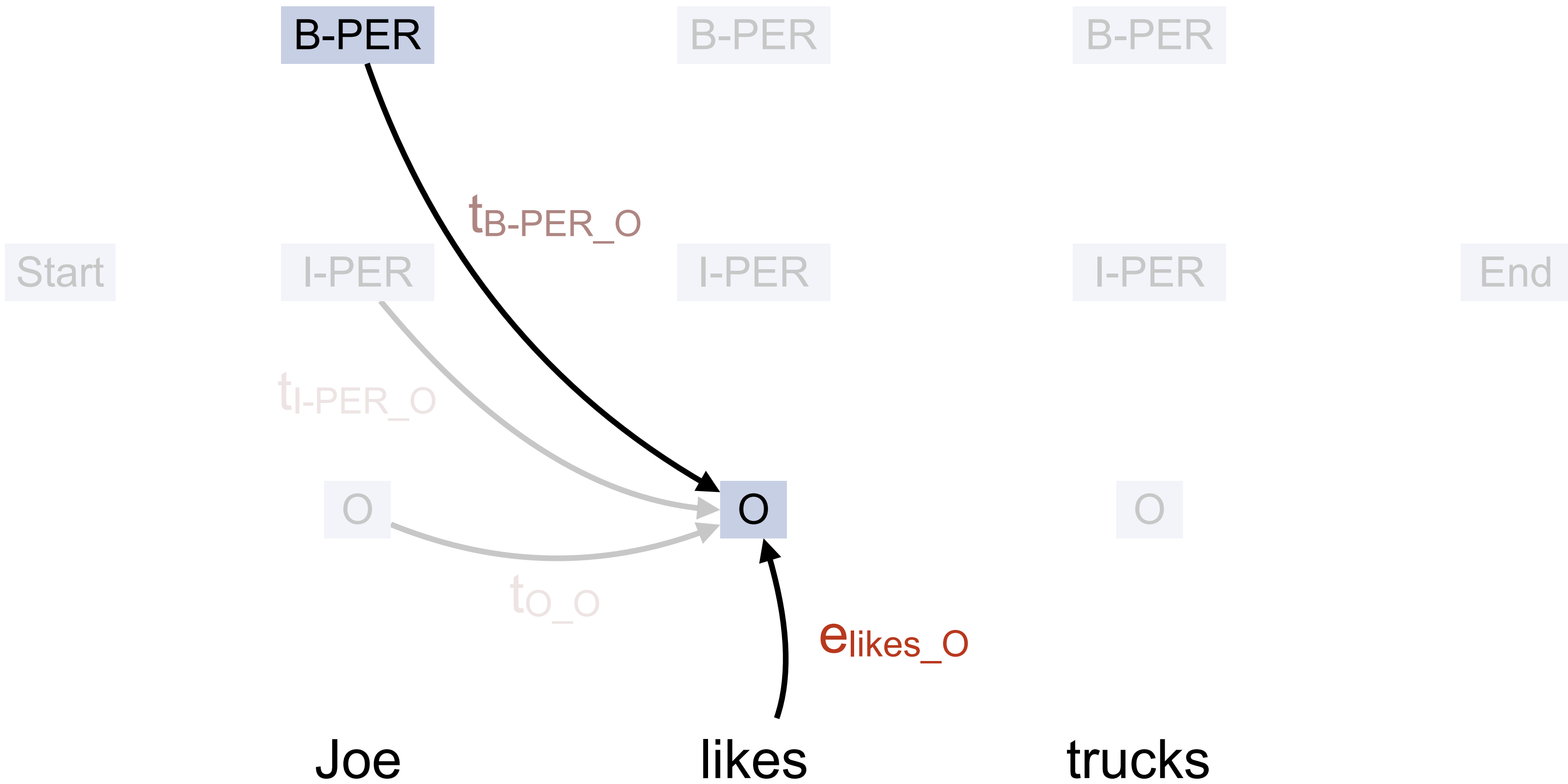
We calculate intermediate scores, then continuations, noting the best

$$\text{prob}_6 = e_{\text{likes\_O}} * \max(t_{\text{prev\_O}} * \text{prob}_{\text{prev}})$$



prob_1	Start
prob_2	Start
prob_3	Start

prob_4	O
prob_5	B-PER
prob_6	B-PER

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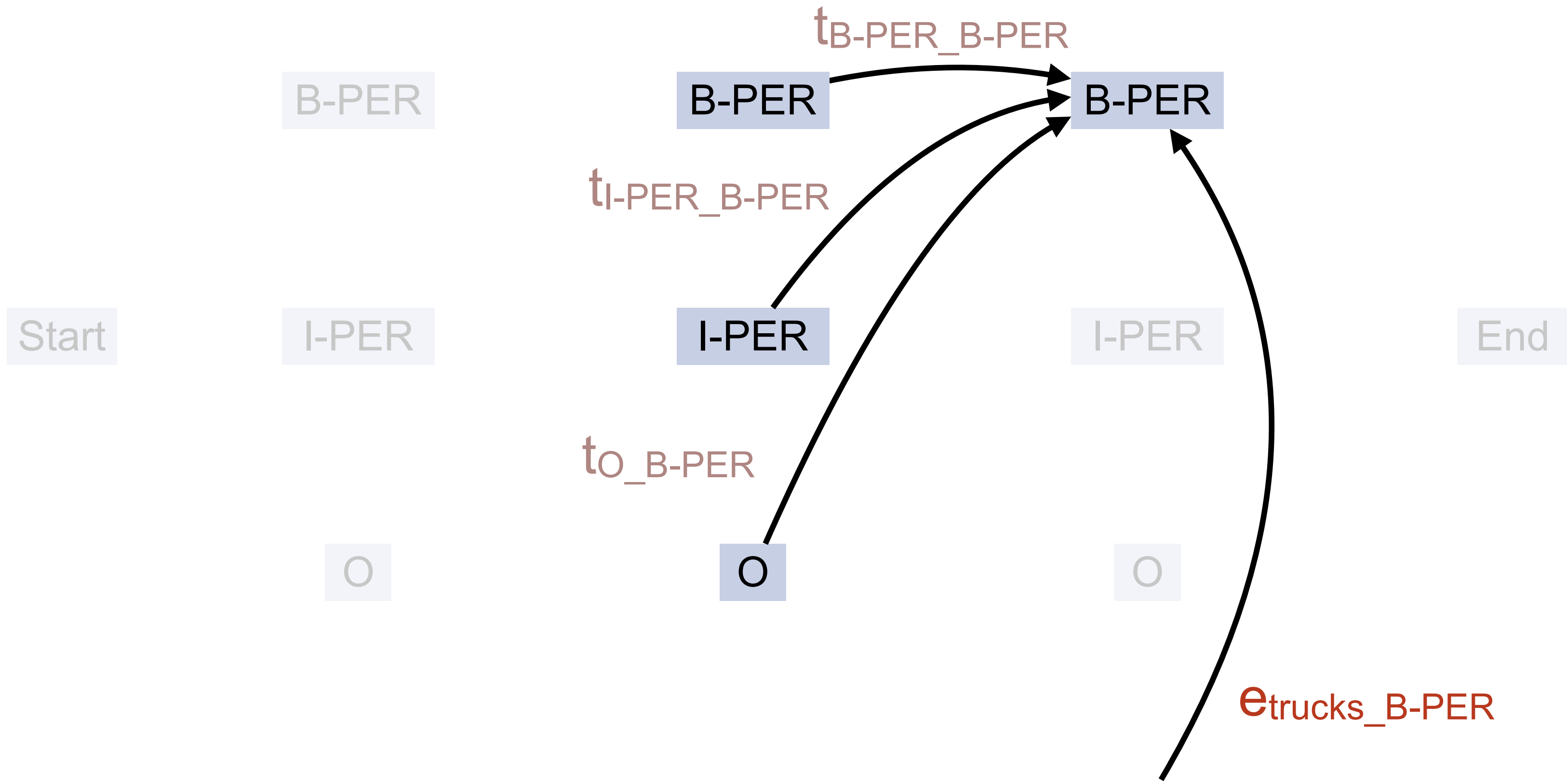
Each step only looks back one step

$$prob_7 = e_{trucks\_B\text{-}PER} * \max(t_{prev\_B\text{-}PER} * prob_{prev})$$



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	

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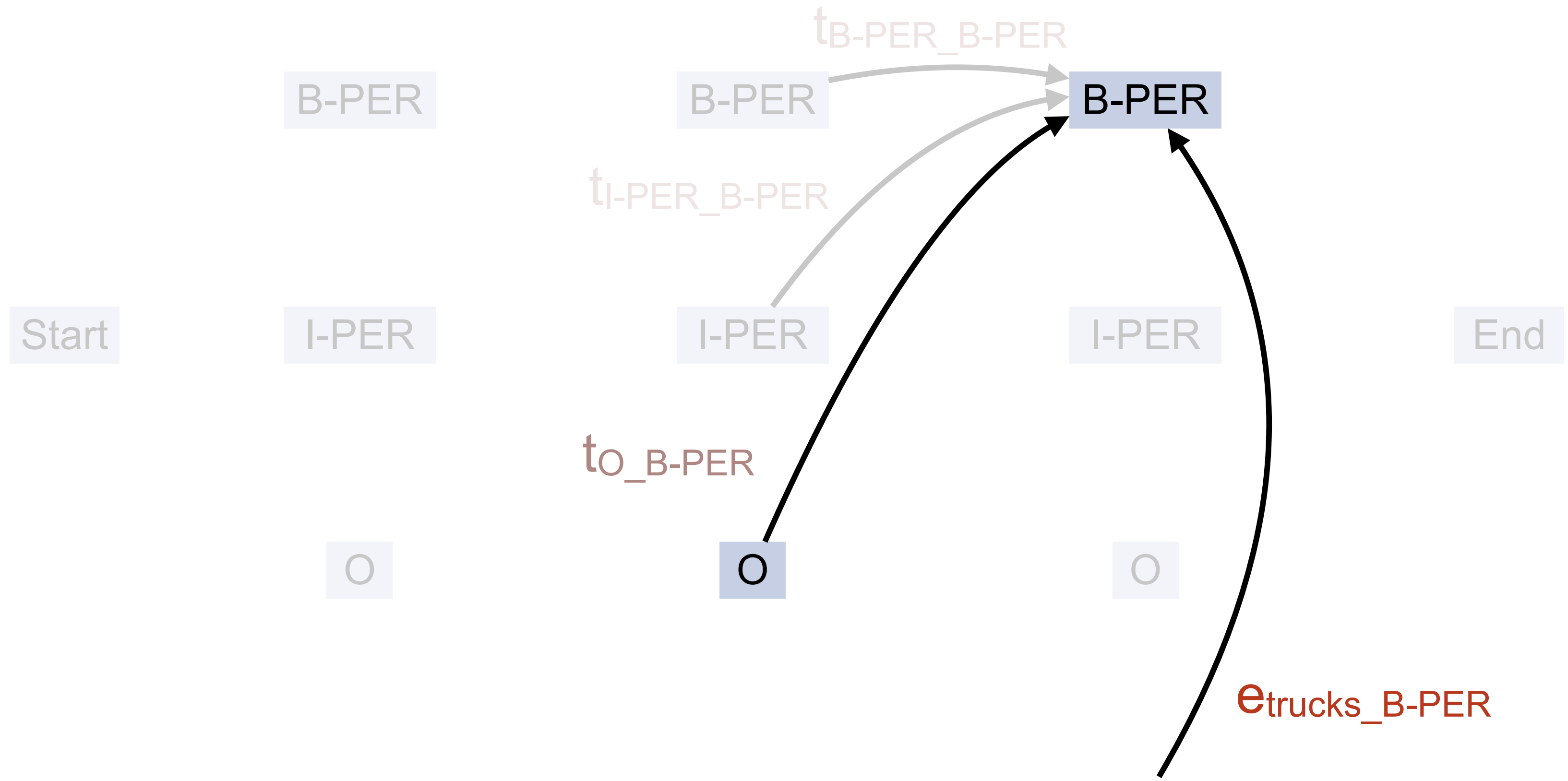
Each step only looks back one step

$$prob_7 = e_{trucks\_B\text{-}PER} * \max(t_{prev\_B\text{-}PER} * prob_{prev})$$



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	O

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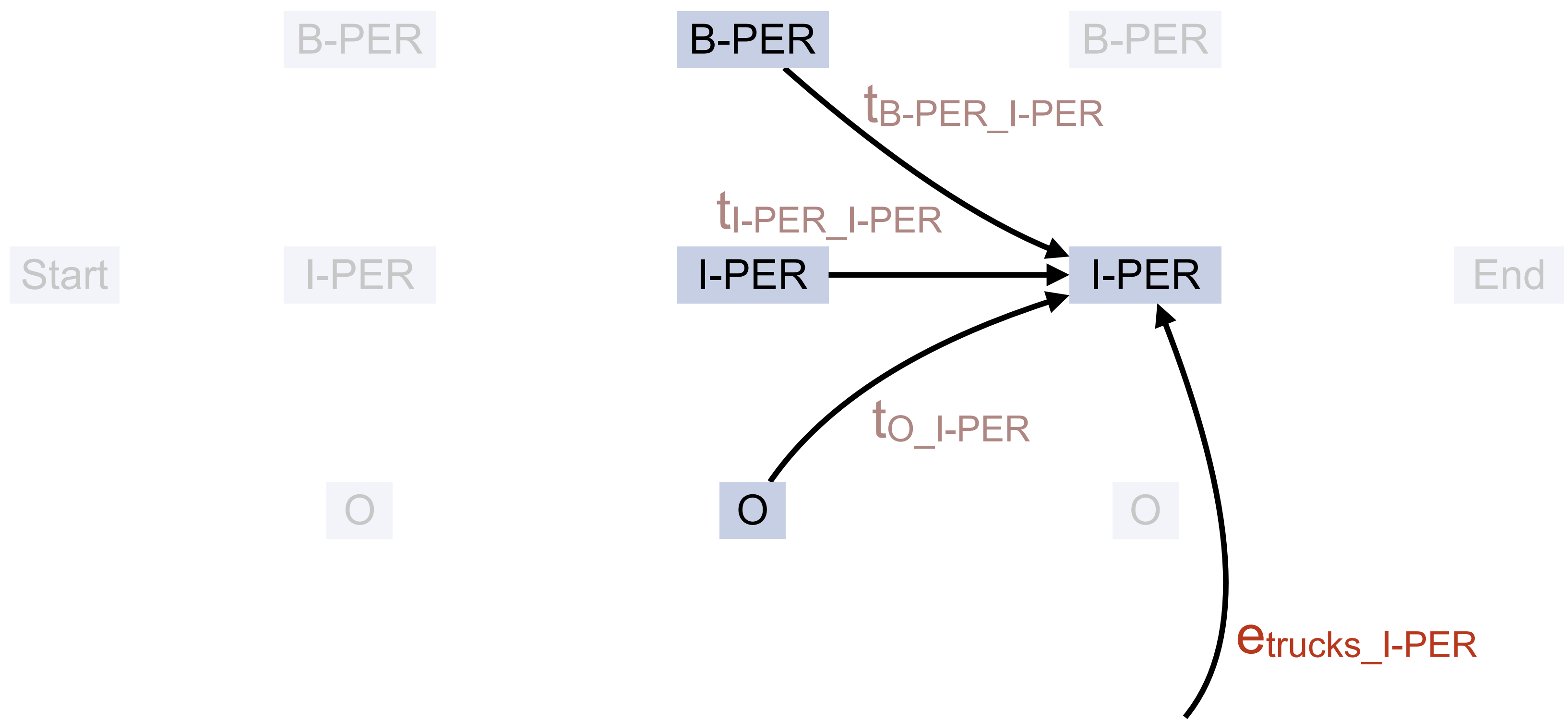
Each step only looks back one step

$$prob_8 = e_{trucks\_I\text{-}PER} * \max(t_{prev\_I\text{-}PER} * prob_{prev})$$



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

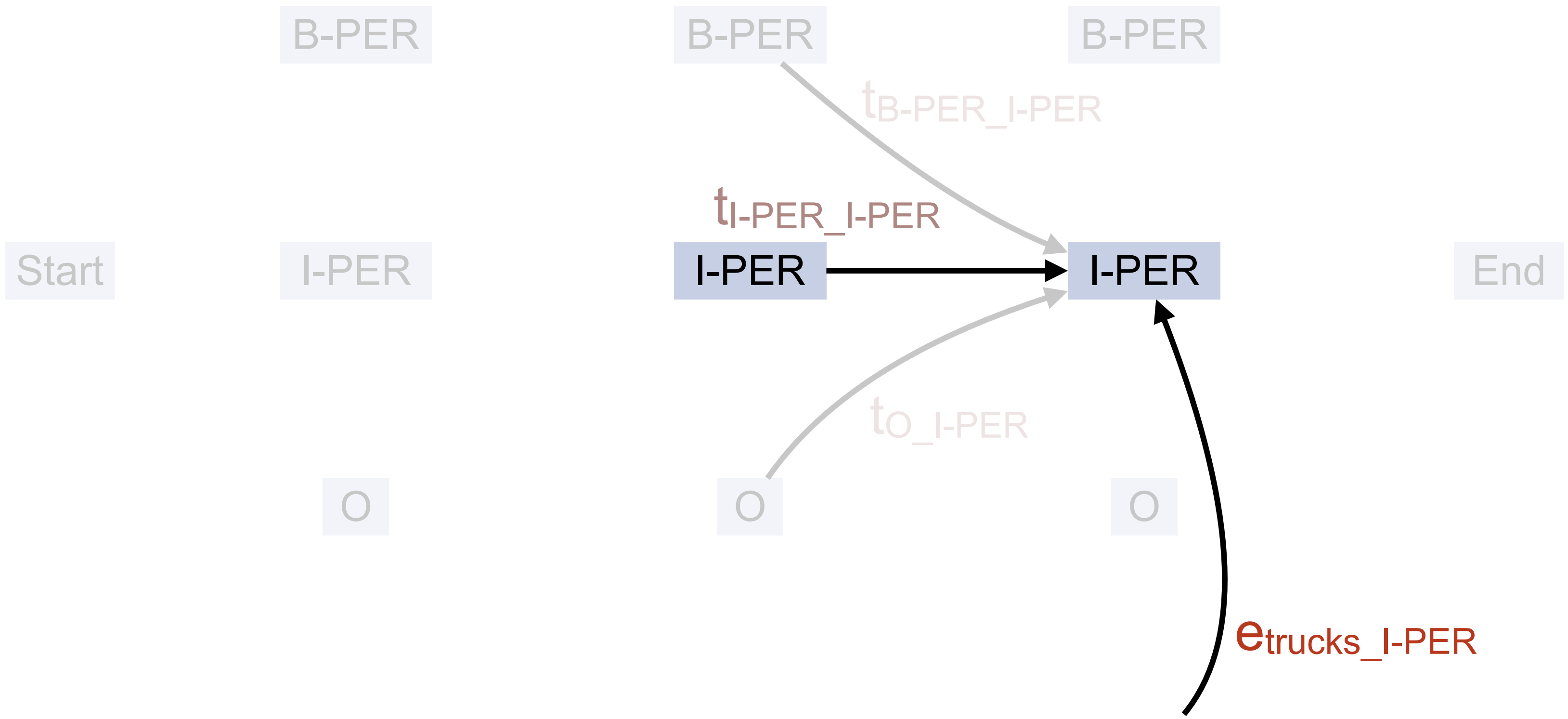
$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	O
$prob_8$	

Each step only looks back one step

$$prob_8 = e_{trucks\_I\text{-}PER} * \max(t_{prev\_I\text{-}PER} * prob_{prev})$$



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	O
$prob_8$	I-PER

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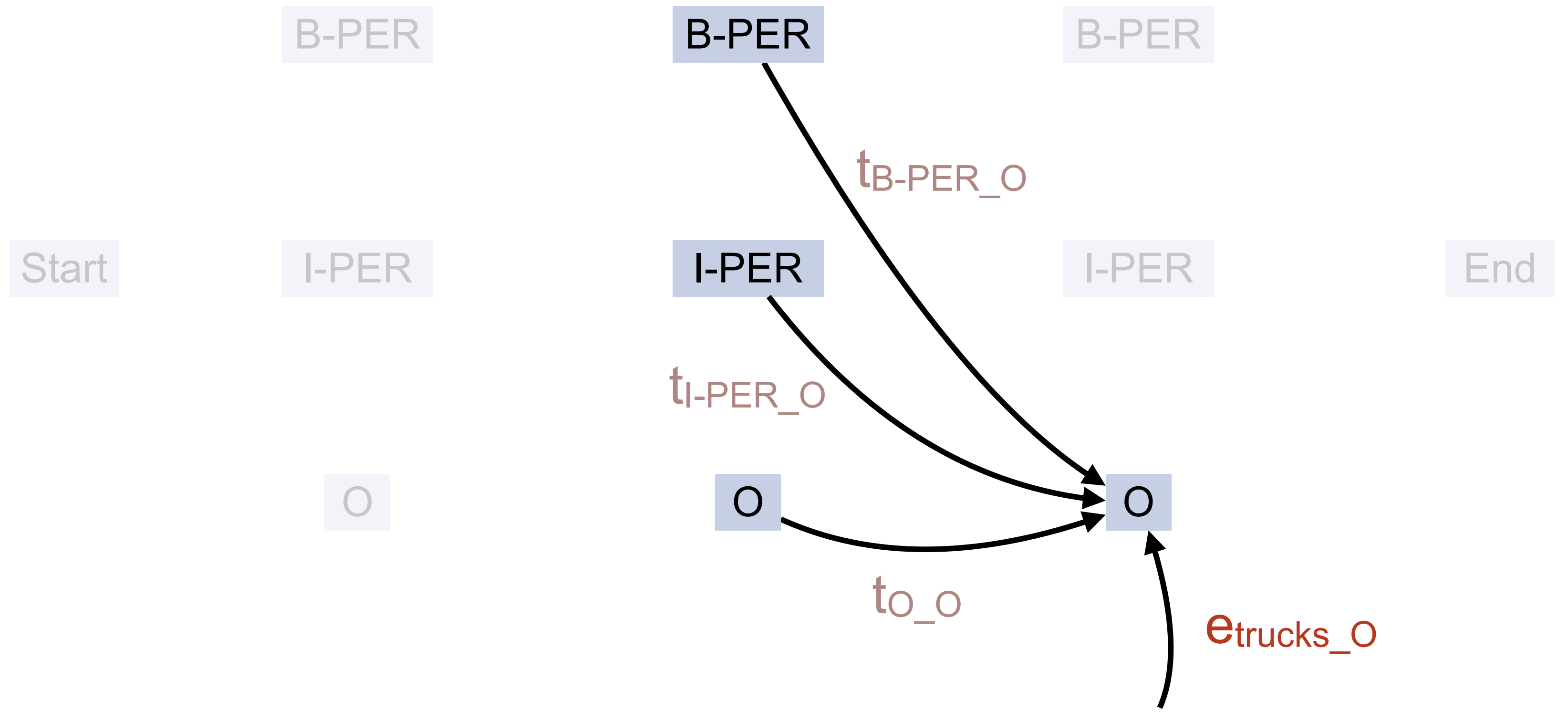
Each step only looks back one step

$$prob_9 = e_{trucks\_I\text{-}PER} * \max(t_{prev\_I\text{-}PER} * prob_{prev})$$



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	O
$prob_8$	I-PER
$prob_9$	

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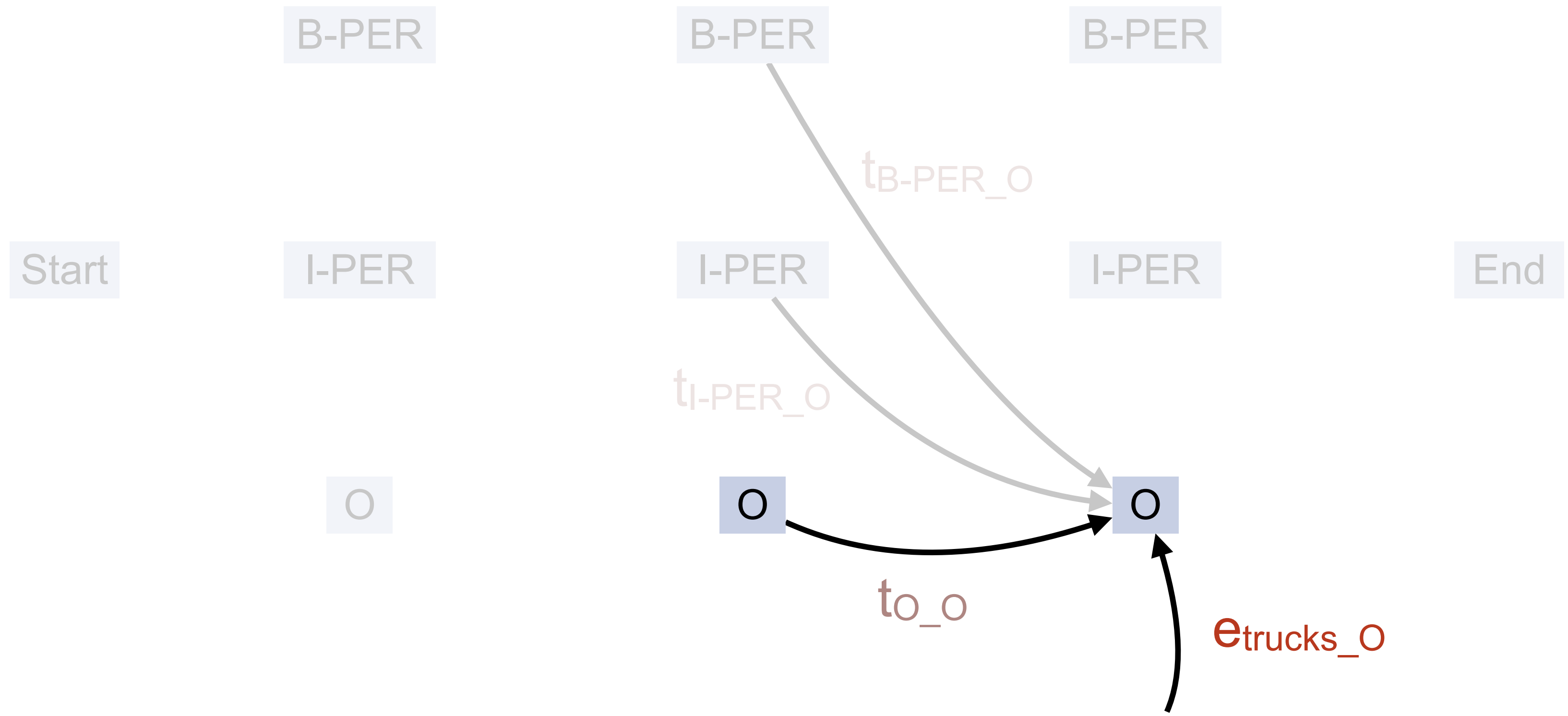
Each step only looks back one step

$$prob_9 = e_{trucks\_I\text{-}PER} * \max(t_{prev\_I\text{-}PER} * prob_{prev})$$



Joe	
$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes	
$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks	
$prob_7$	O
$prob_8$	I-PER
$prob_9$	O

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Ending

Each step only looks back one step

$$\boxed{prob_{10} = \max(t_{prev\_End} * prob_{prev})}$$

Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	O
$prob_8$	I-PER
$prob_9$	O

$prob_{10}$	

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Example

Each step only looks back one step

t_{O_End} $prob_9$

$$prob_{10} = \max(t_{prev\_End} * prob_{prev})$$

Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	O
$prob_8$	I-PER
$prob_9$	O

$prob_{10}$	O

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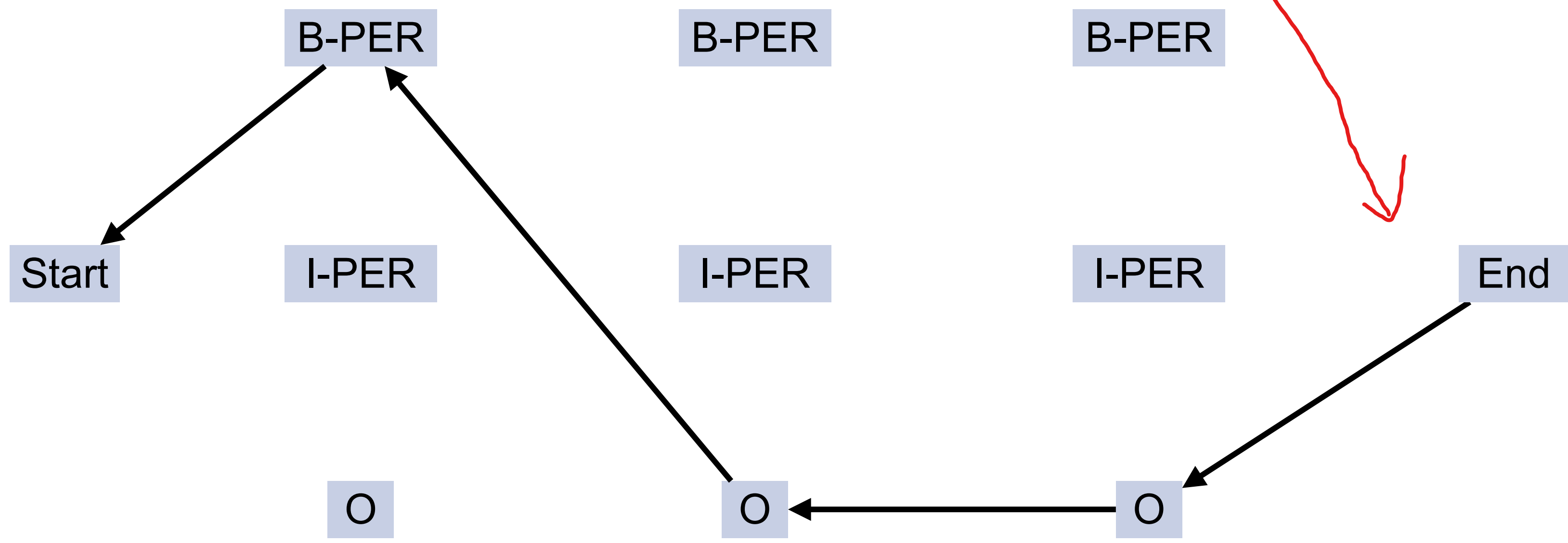
To get the path, follow the references backwards to the start



Joe

$prob_1$	Start
$prob_2$	Start
$prob_3$	Start

likes

$prob_4$	O
$prob_5$	B-PER
$prob_6$	B-PER

trucks

$prob_7$	O
$prob_8$	I-PER
$prob_9$	O

$prob_{10}$	O

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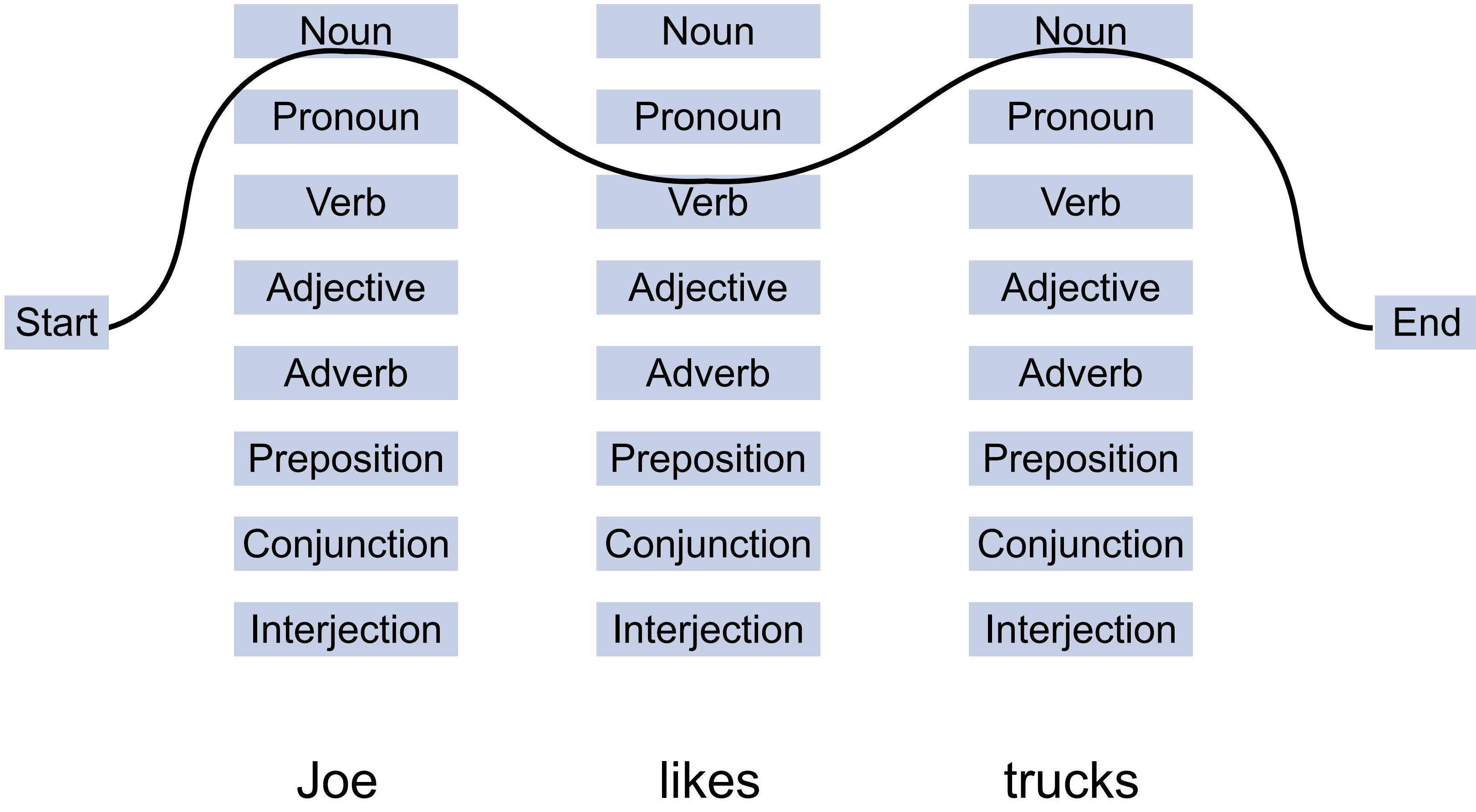
We can apply the same idea to POS tagging



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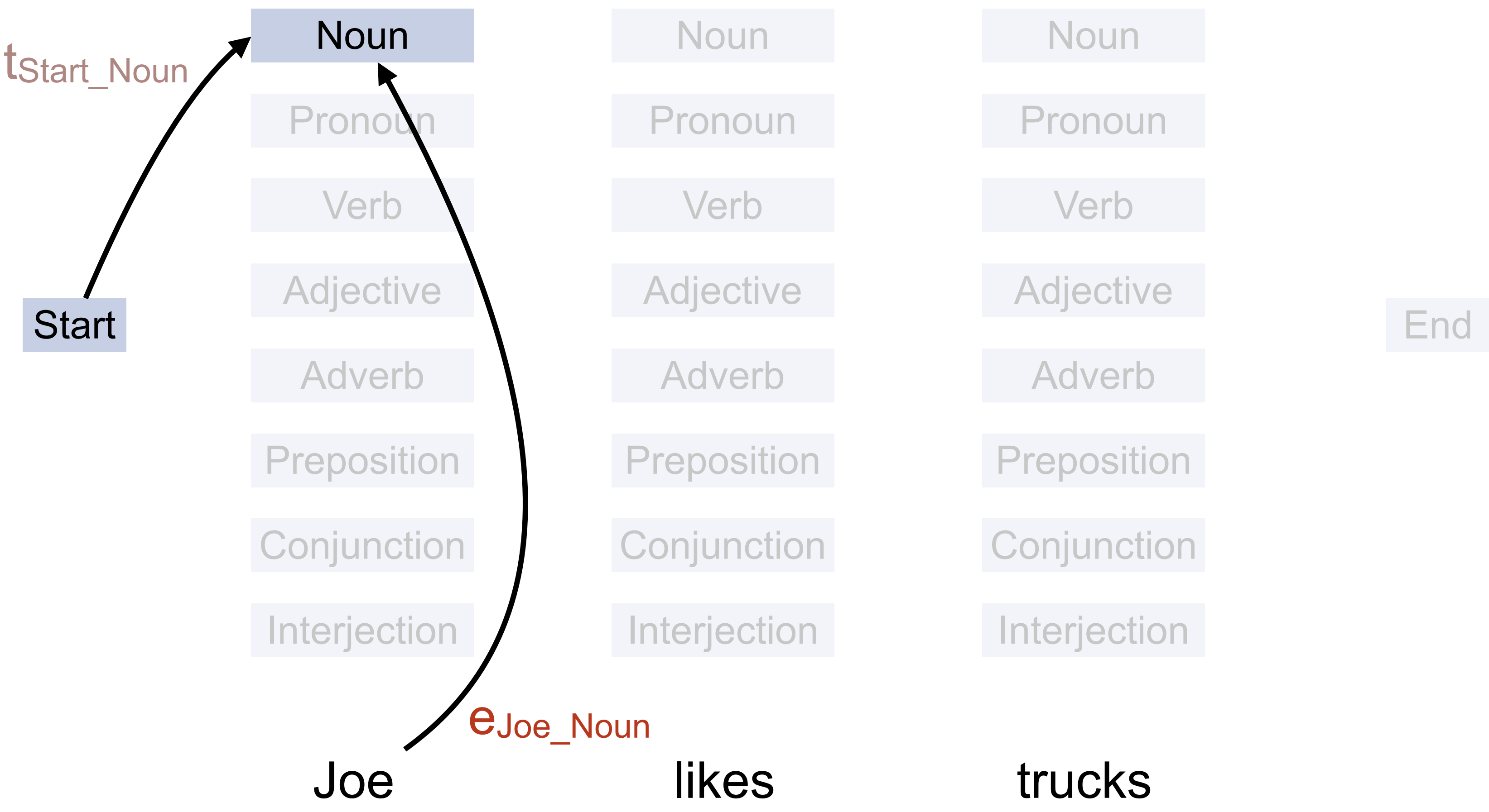
One more example

We can apply the same idea to POS tagging



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Forward

Pseudocode for the algorithm to calculate scores and previous labels

```
Create storage for best option for each
(position, label) pair

For each position in input:
    For each label:
        Best score = -infinity
        Best previous = None
        For each previous_label:
            Score = previous_label's prob *
                    prob(label | input and
                    previous label)
            If score is better than best:
                Update best
        Save best score and best previous for
        this (position, label) pair
```

Called the Viterbi algorithm

(note, also need to account for start and end)

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Pseudocode for the algorithm to get the path

path back

```
Path = []
Current label = End
For position from end of sequence to start:
    Current label = Best for this position and
                    the current label
    Append current label to Path

Reverse path
```

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Time complexity is $\boxed{O(|words| * |labels|^2)}$

Joe, likes, trucks

|words| steps

B-PER
I-PER
O
likes

In each step, consider |labels|

O

For each option, consider |labels| previous options similar to Perceptron

ex. backprob

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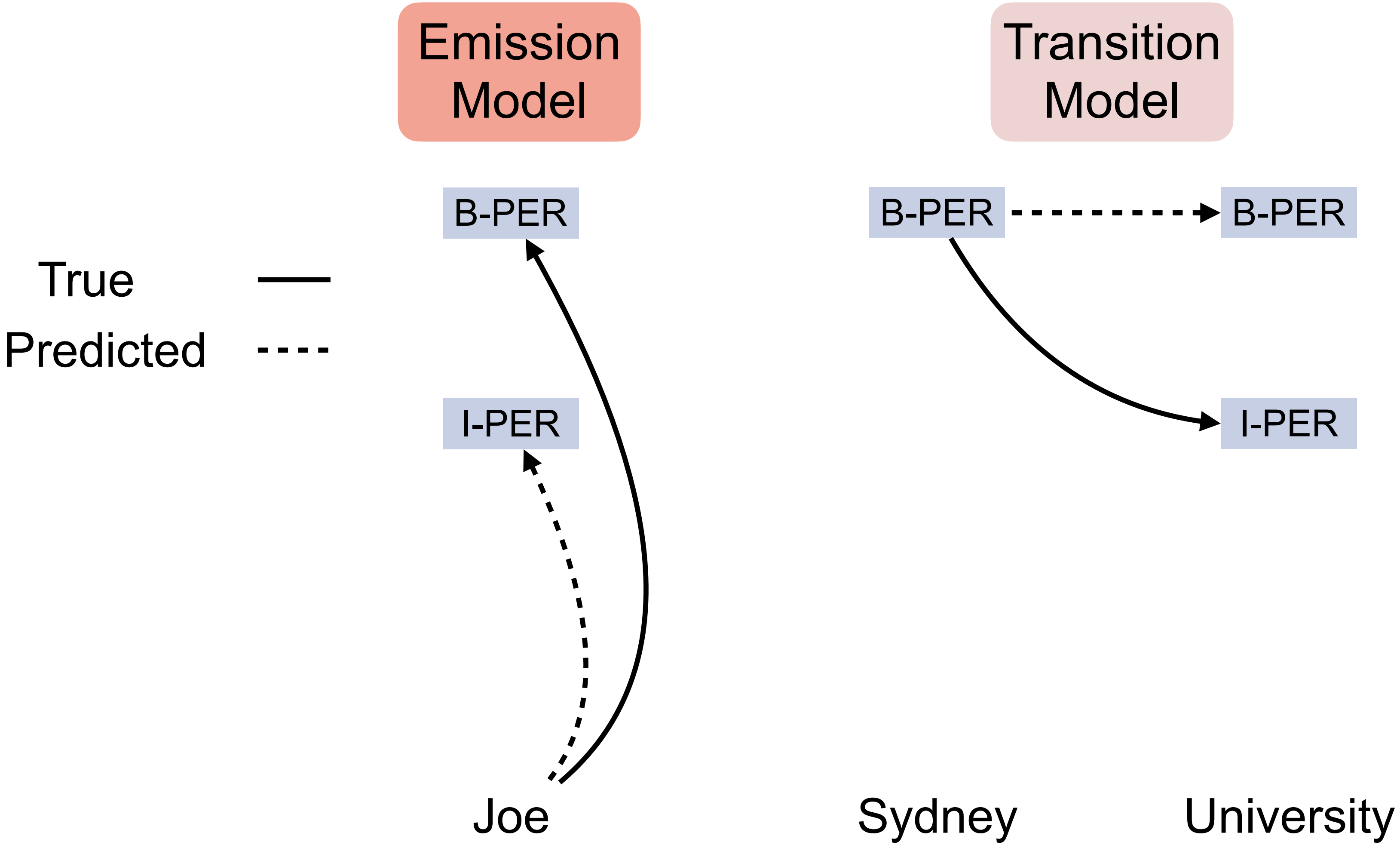
Learn by comparing the final output with the true answer



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The model can use all of the input, and the previous label

Emission Model

O

e_{likes_O}

Joe likes trucks

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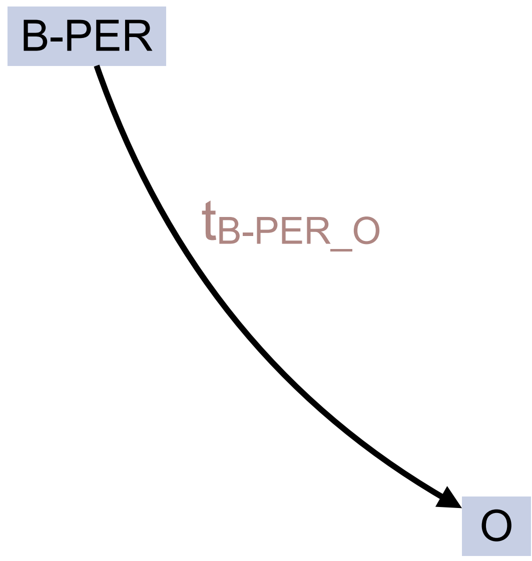
The model can use all of the input, and the previous label

Transition Model



Joe likes trucks

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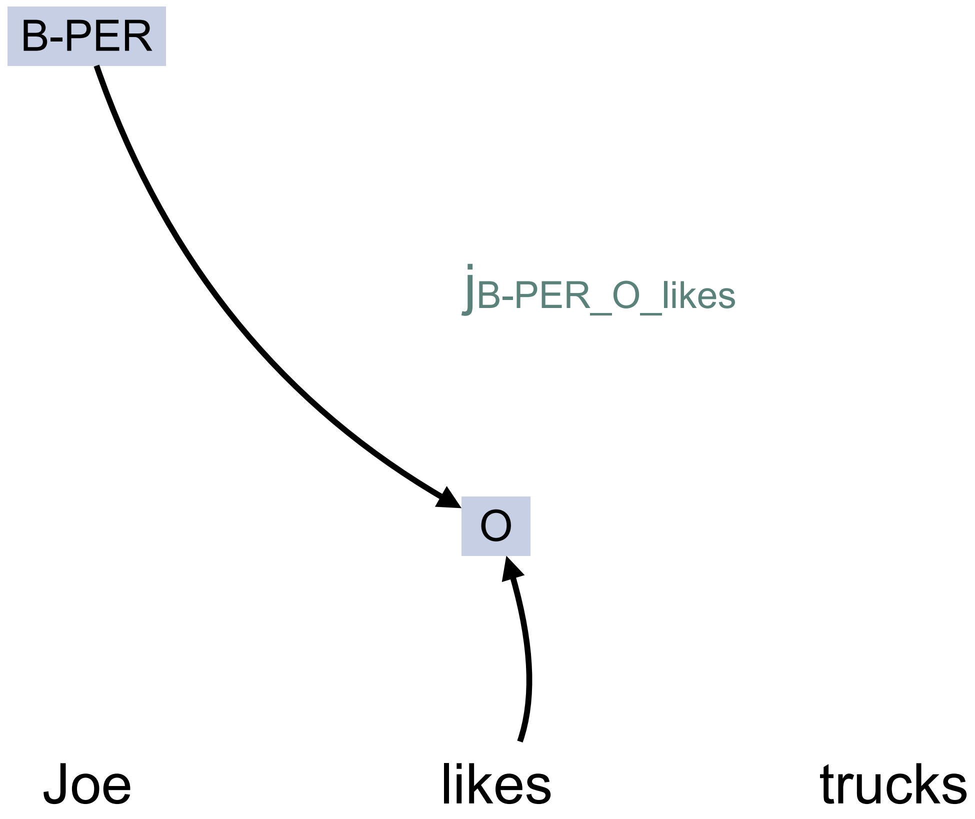
We can also define a model that does both scores at once

Joint Model

$$\text{score}_{\text{current}} = \max(j_{\text{prev\_label\_word}} * \text{score}_{\text{prev}})$$



If we are willing to increase complexity, we can use more label context

Previous_Current

	Joe	likes	trucks	
		B-PER_B-PER	B-PER_B-PER	
		I-PER_B-PER	I-PER_B-PER	
		O_B-PER	O_B-PER	
	Start_B-PER	B-PER_I-PER	B-PER_I-PER	
Start	Start_I-PER	I-PER_I-PER	I-PER_I-PER	End
	Start_O	O_I-PER	O_I-PER	
		B-PER_O	B-PER_O	
		I-PER_O	I-PER_O	
		O_O	O_O	

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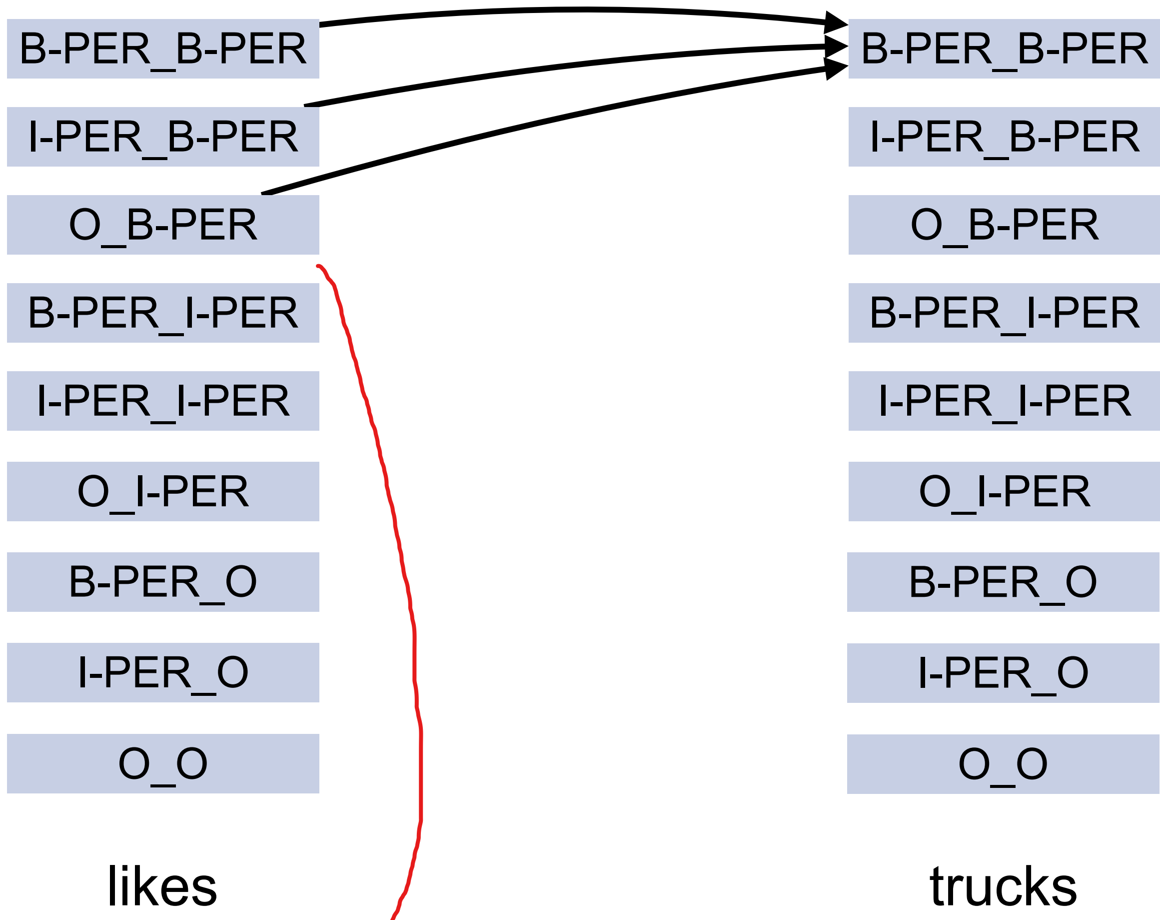
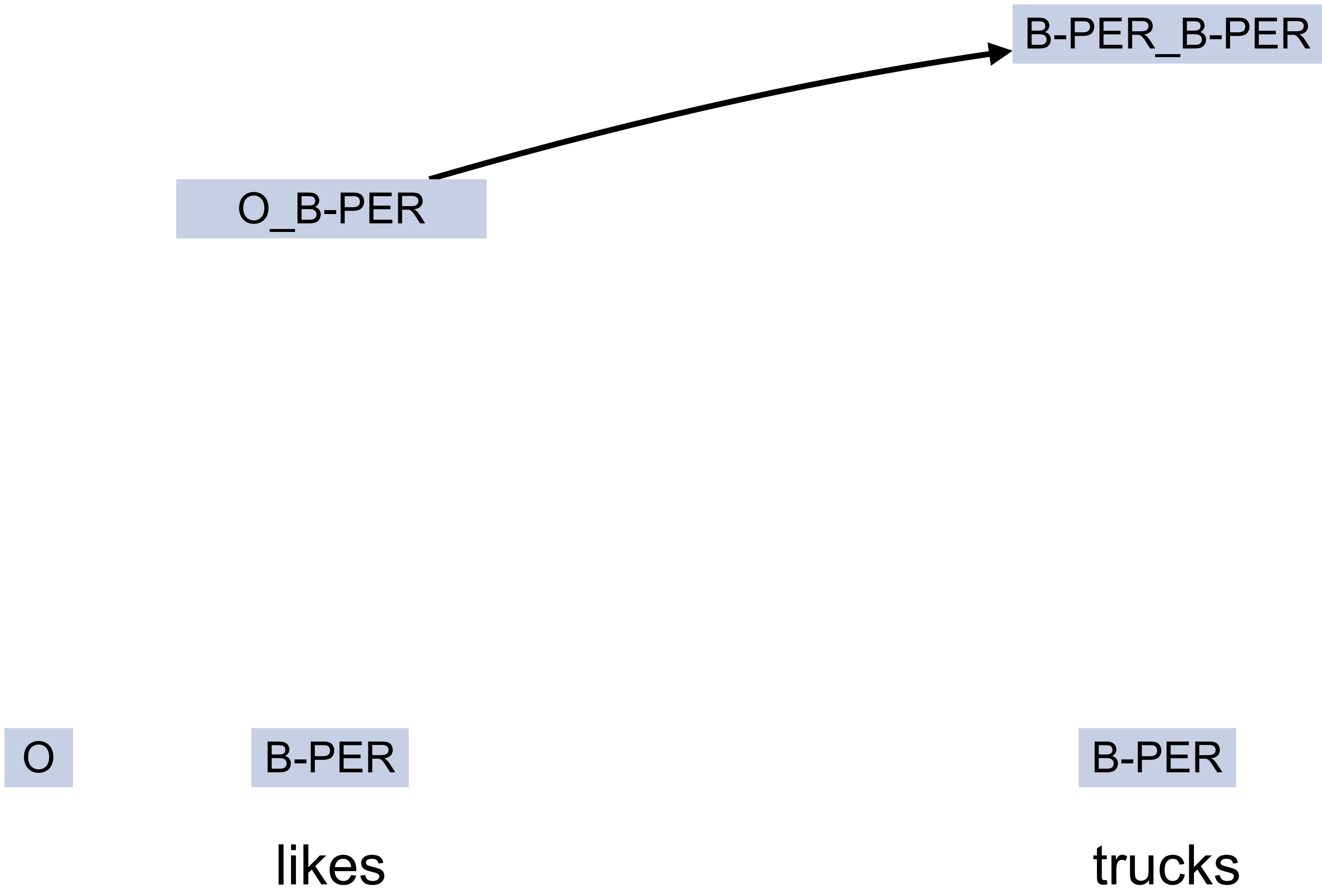
If we are willing to increase complexity, we can use more label context



more complex, can aware
before token

If we are willing to increase complexity, we can use more label context



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Now, time complexity is $\boxed{O(|words| * |labels|^3)}$

difference

Joe, likes, trucks

|words| steps

B-PER_B-PER

I-PER_B-PER

O_B-PER

…

likes

In each step, consider |labels|*|labels|

O

For each option, consider |labels| previous options

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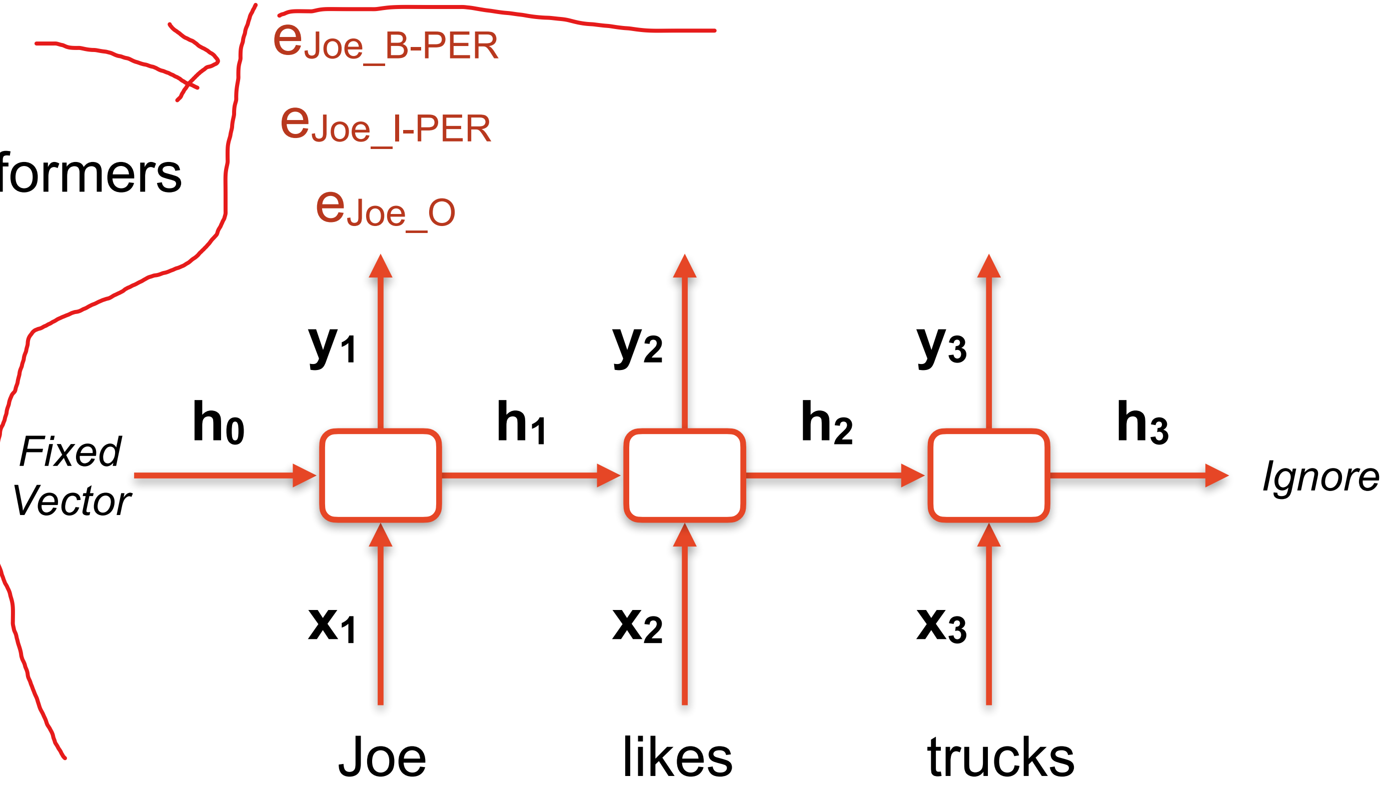
We can apply this method to a variety of models

Linear models (e.g., CRF)

Feedforward Networks

RNNs

Transformers



3 minute Break - stretch and visit Menti

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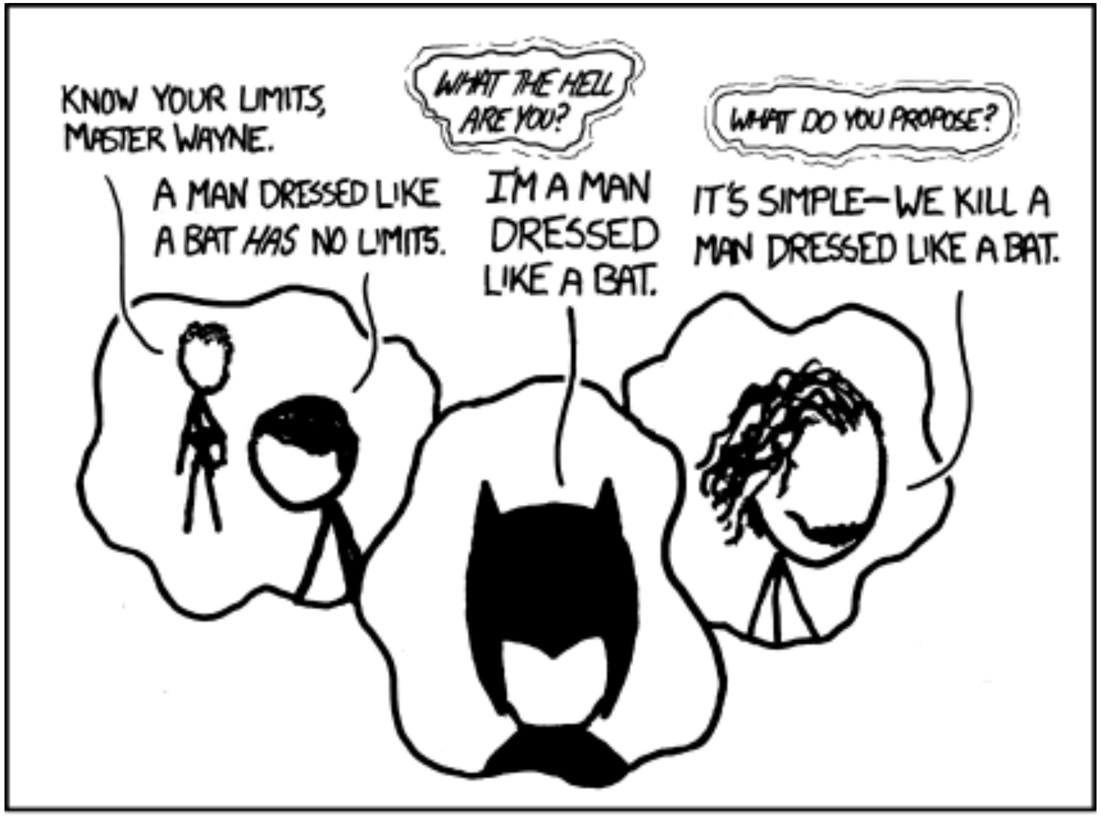

MY HOBBY:
WHENEVER ANYONE SAYS "BATMAN", I MENTALLY REPLACE IT WITH "A MAN DRESSED LIKE A BAT."

Batman

[I'm really worried Christopher Nolan will kill a man dressed like a bat in his next movie. (The man will be dressed like a bat, I mean. Christopher Nolan won't be, probably.)]

Source: https://xkcd.com/1004/

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Graph Parsing

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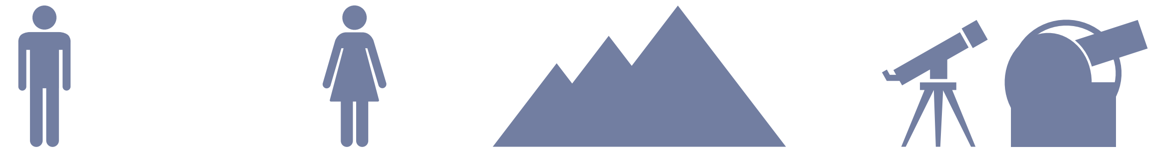
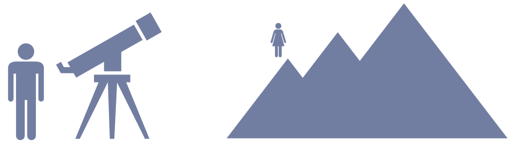
Syntactic parsing can resolve ambiguities



I saw the person on the hill with a telescope

3 meanings



I saw the person on the hill with a telescope

I saw the person on the hill with a telescope

I saw the person on the hill with a telescope

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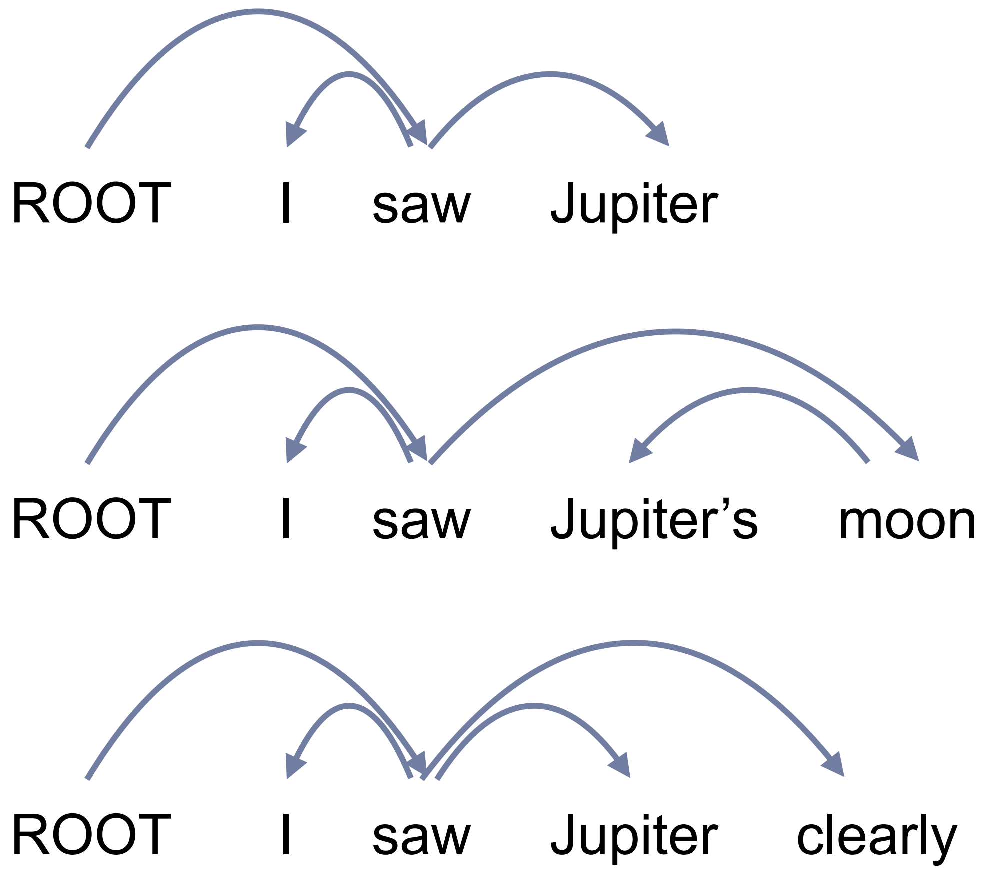
Arcs / Edges / Dependencies go from a head to a dependent



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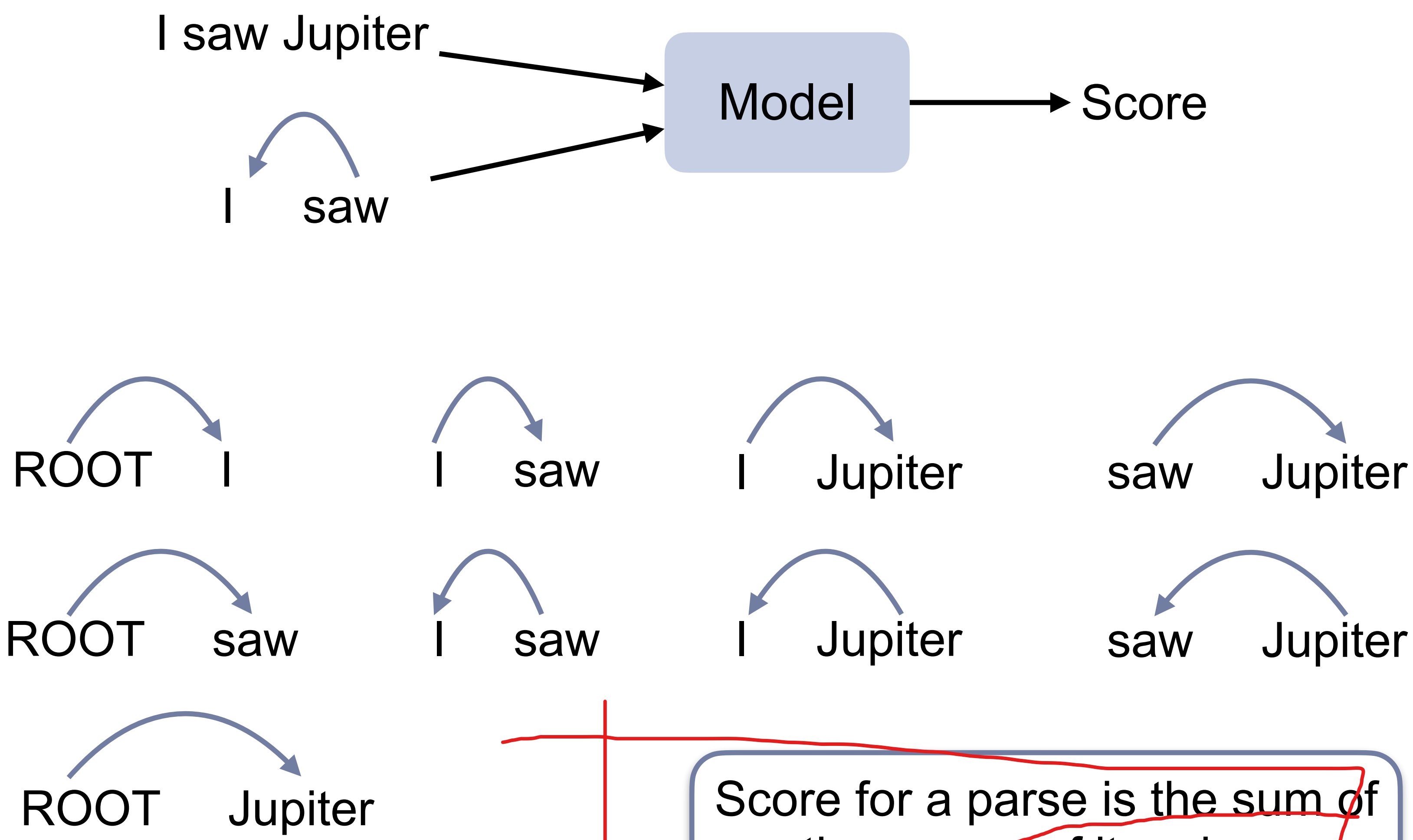
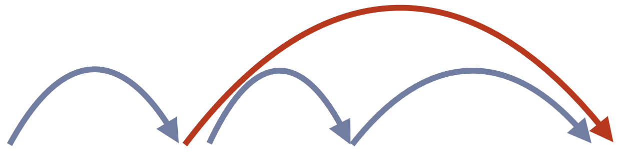
We'll use an arc model to score options



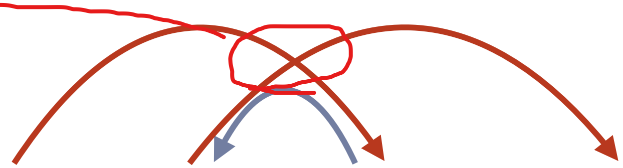
Score for a parse is the sum of the scores of its edges

Requirements for our inference method

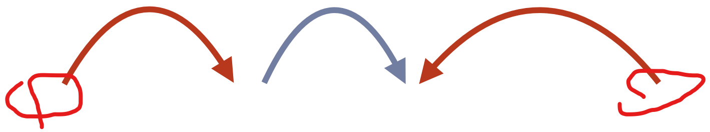
1. Produce a tree



2. No crossing arcs



3. A single root

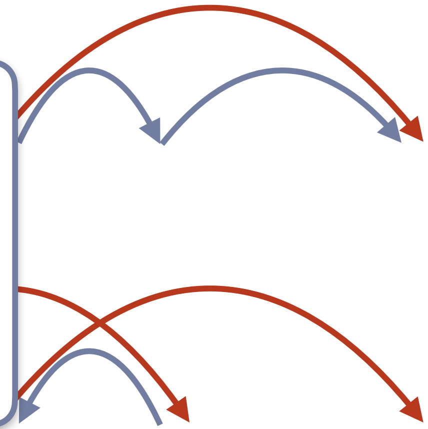


4. The tree has the highest score of all possible trees

Requirements for our inference method

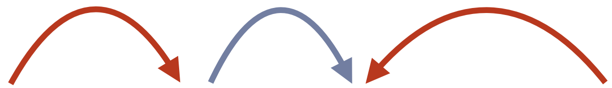
1. Produce a tree

In my research I invented an algorithm that overcomes these two constraints



2. No crossing arcs

3. A single root



4. The tree has the highest score of all possible trees

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Many inference methods - today we see dynamic programming

~~the room for my~~
in ~~my~~ class

boxes meaning in rest pages

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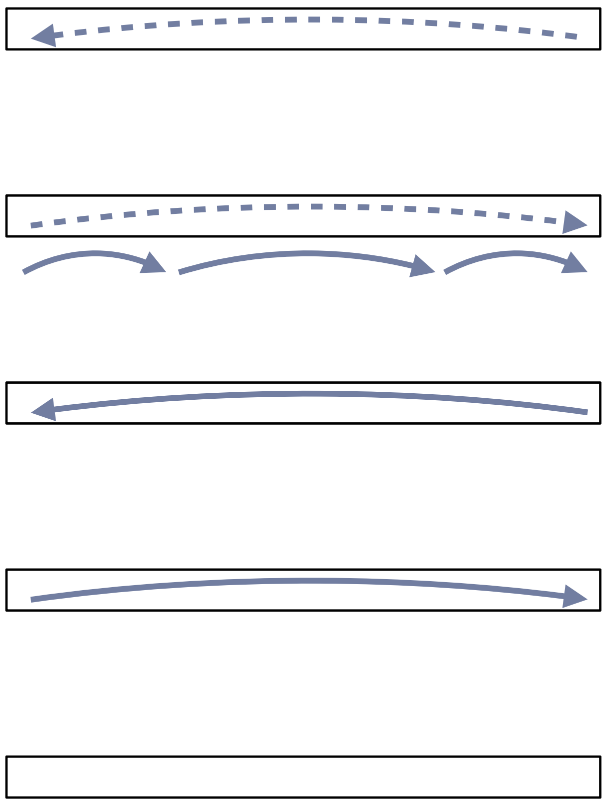
Our inference algorithm is defined by **items** and rules

Item	Represents
	A structure with an **indirect path** from *class* to *in*
	A structure with an **indirect path** from *in* to *class*
	A structure with an **arc** from *class* to *in*
	A structure with an **arc** from *in* to *class*
	A structure with **no link** between *in* and *class*

in … class

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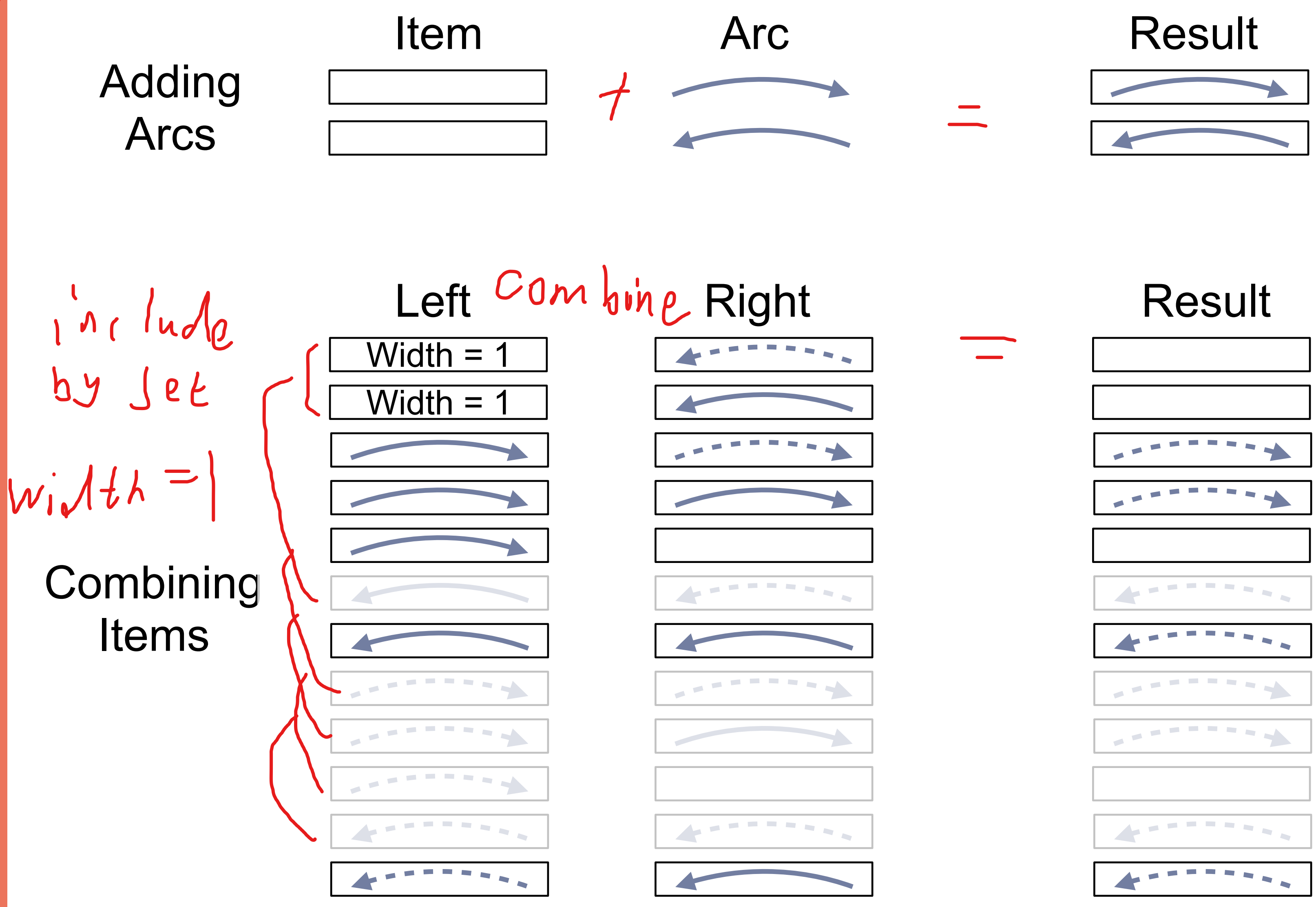
combine

Our inference algorithm is defined by items and **rules**



Example

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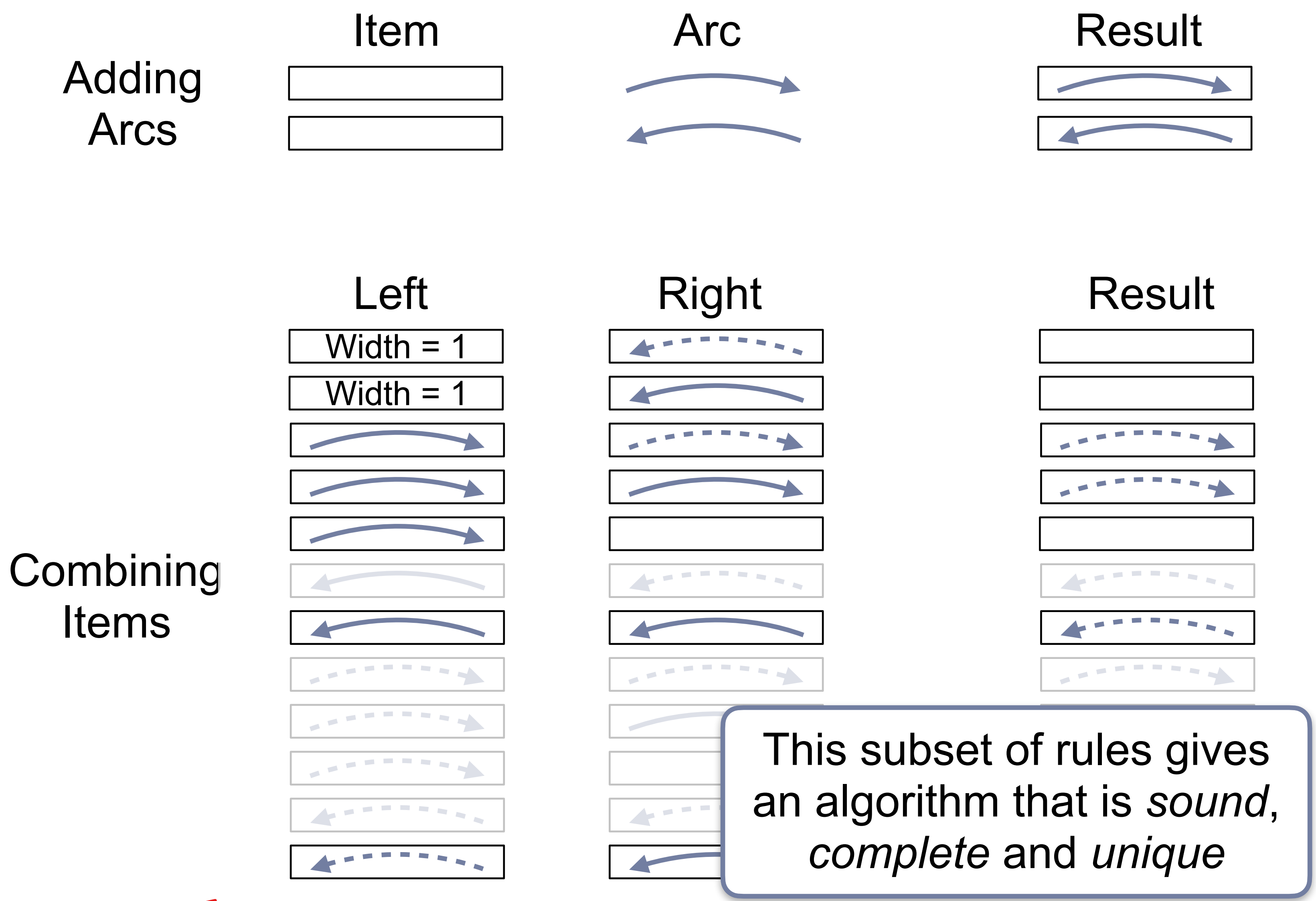
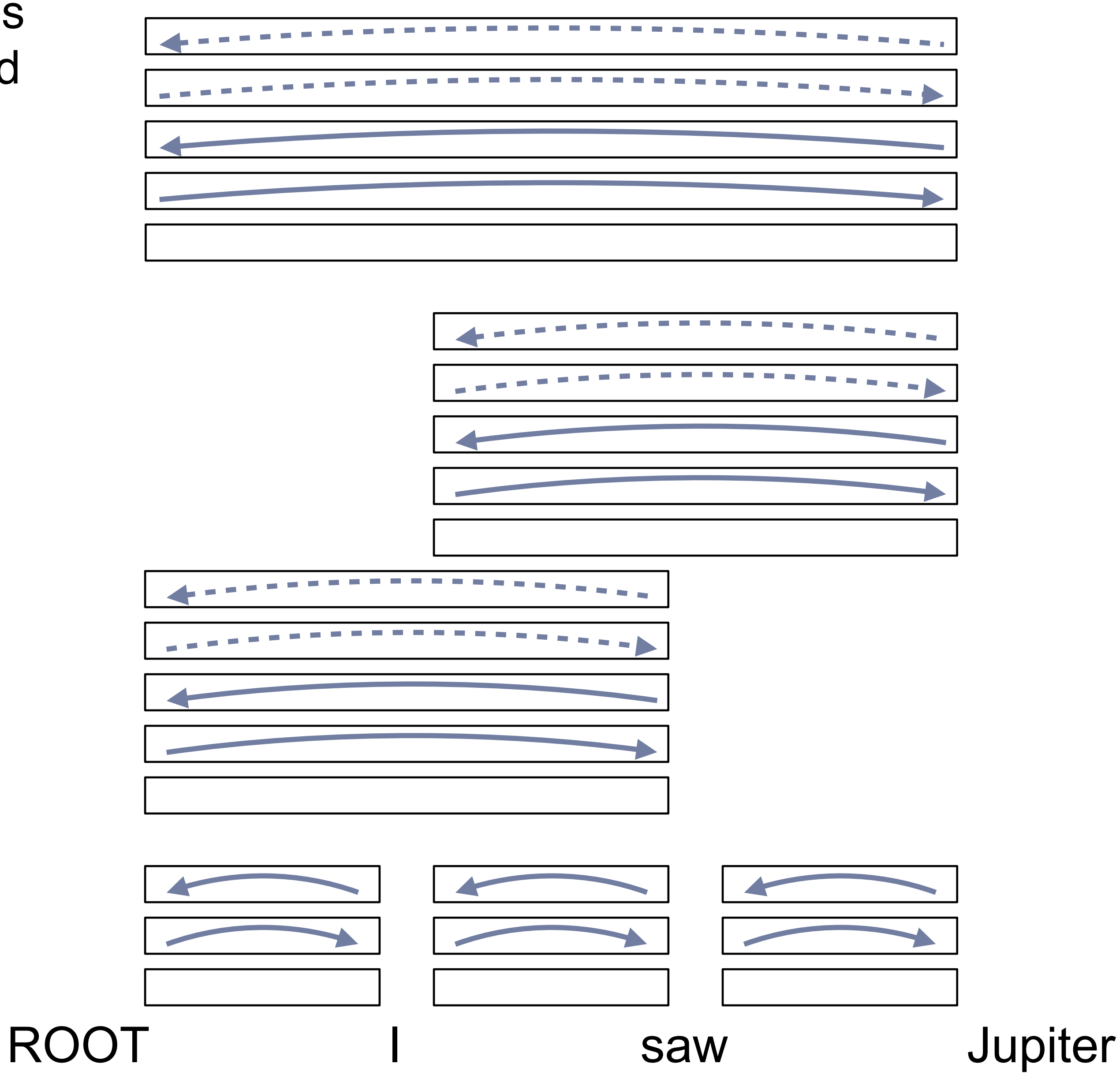
Our inference algorithm is defined by items and **rules**



We use the items and rules to build up the parse



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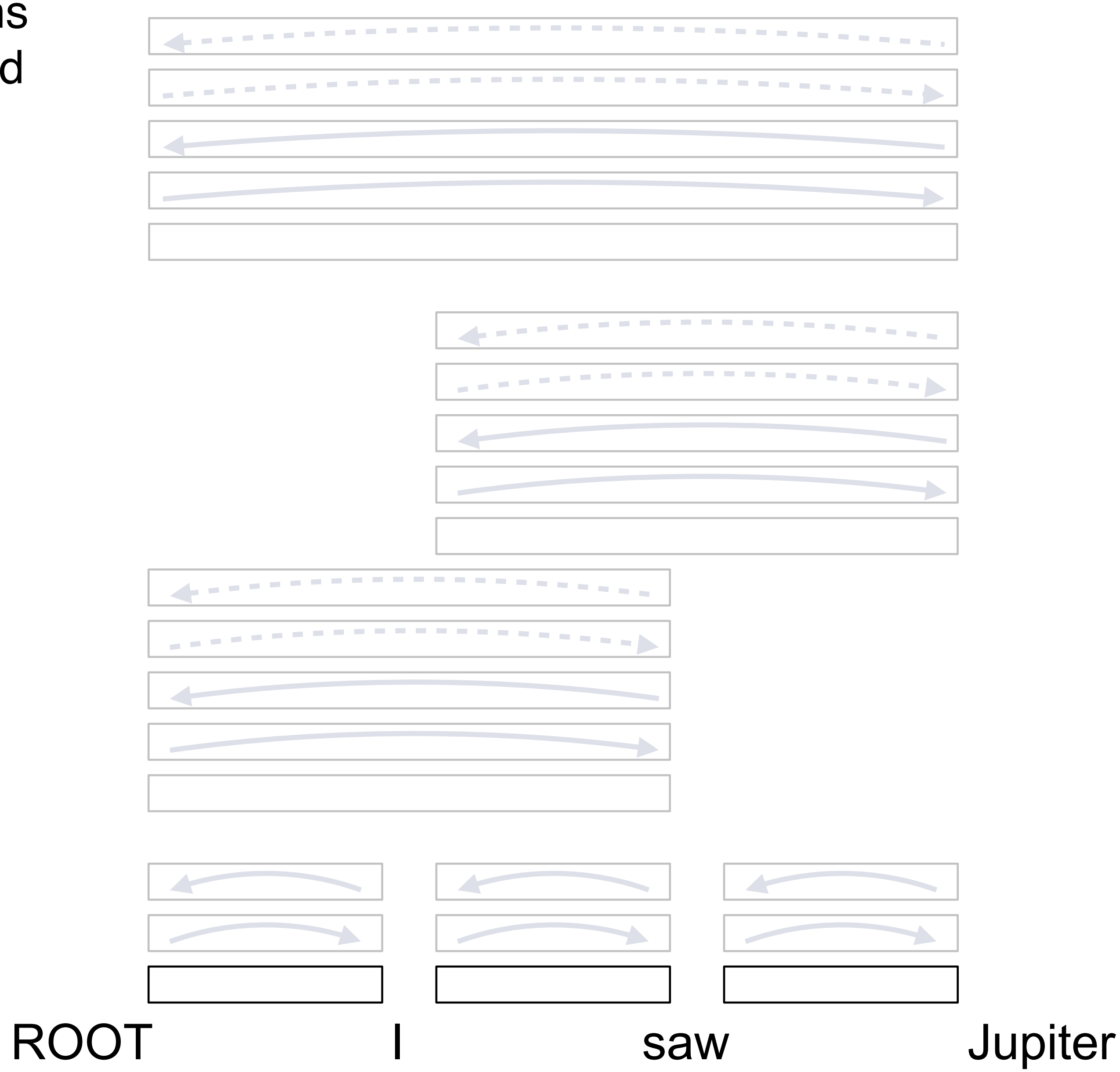
We use the items and rules to build up the parse

Create starting items



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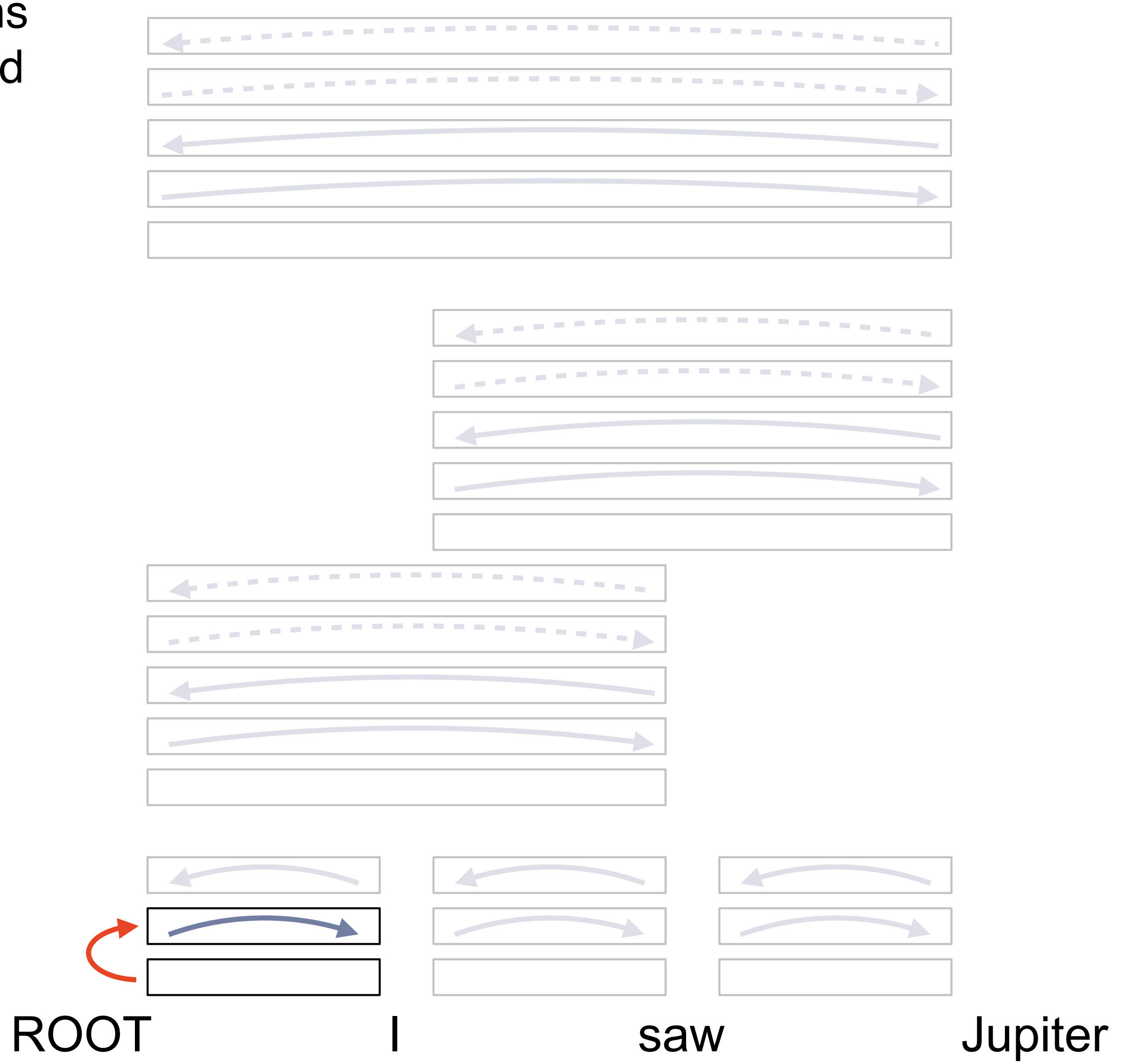
We use the items and rules to build up the parse

2!

Apply arc creation rules



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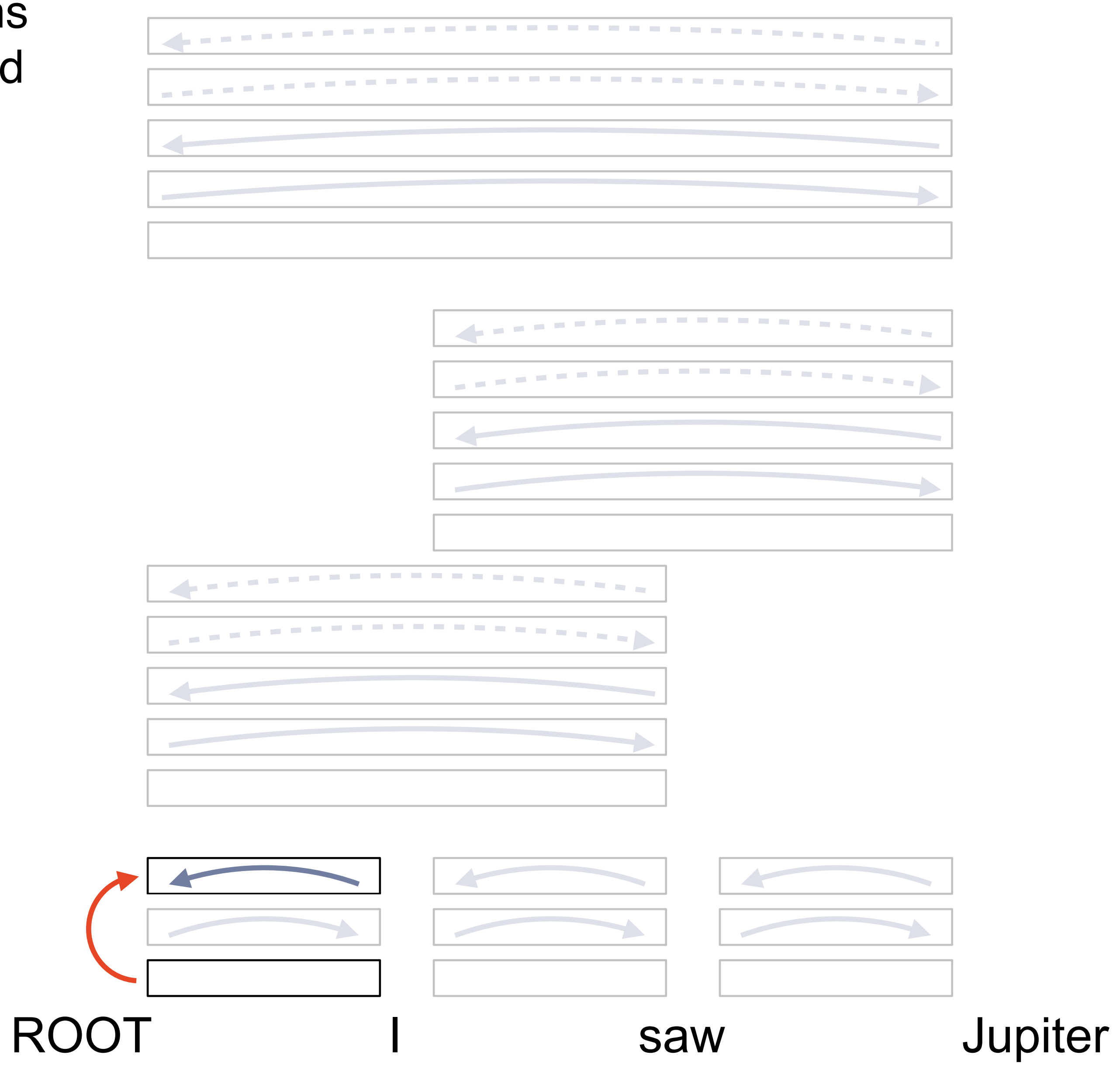
We use the items and rules to build up the parse

Hiding

2.2

Apply arc creation rules



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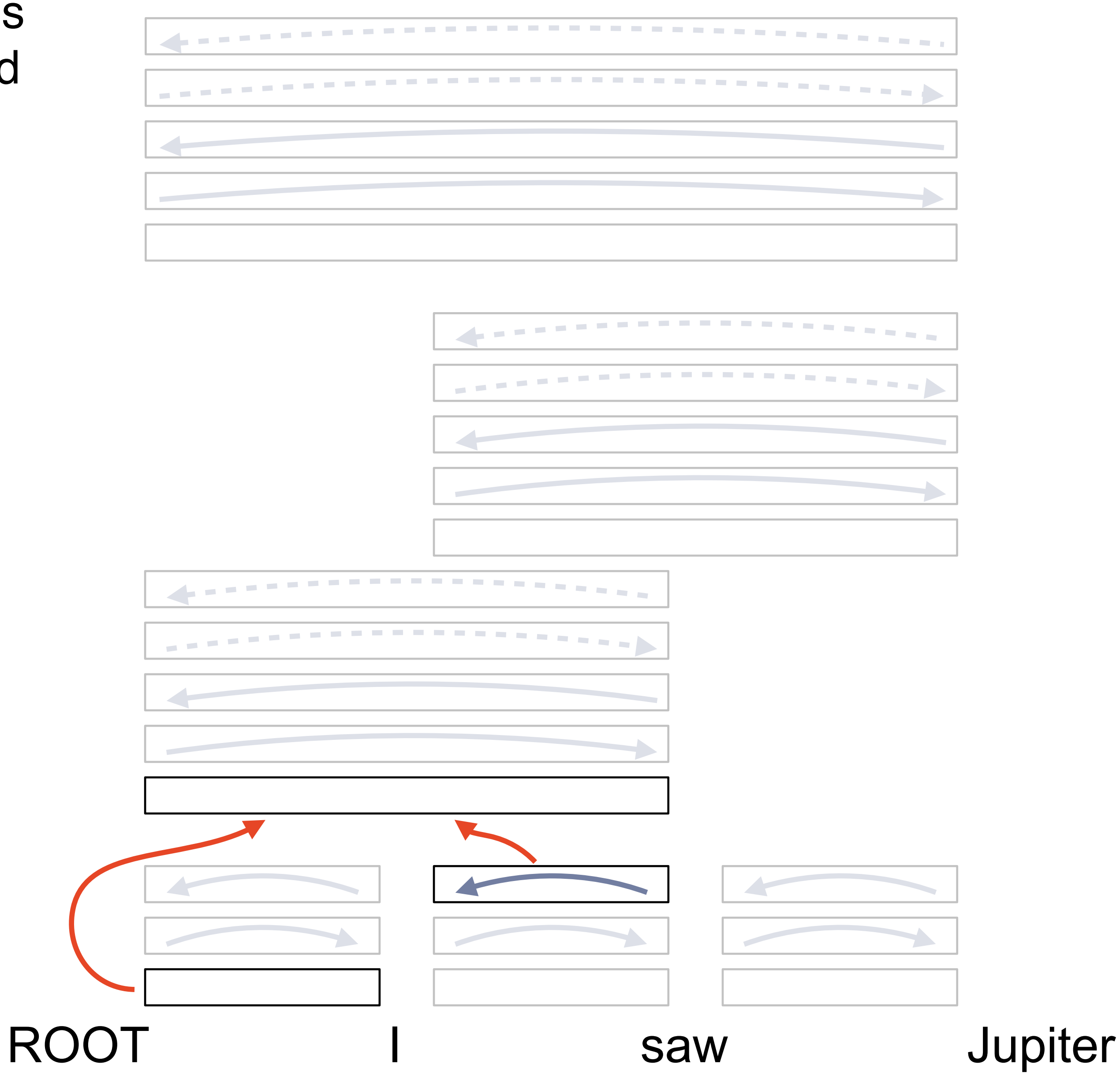
We use the items and rules to build up the parse

Hiding

B

Apply combination rules



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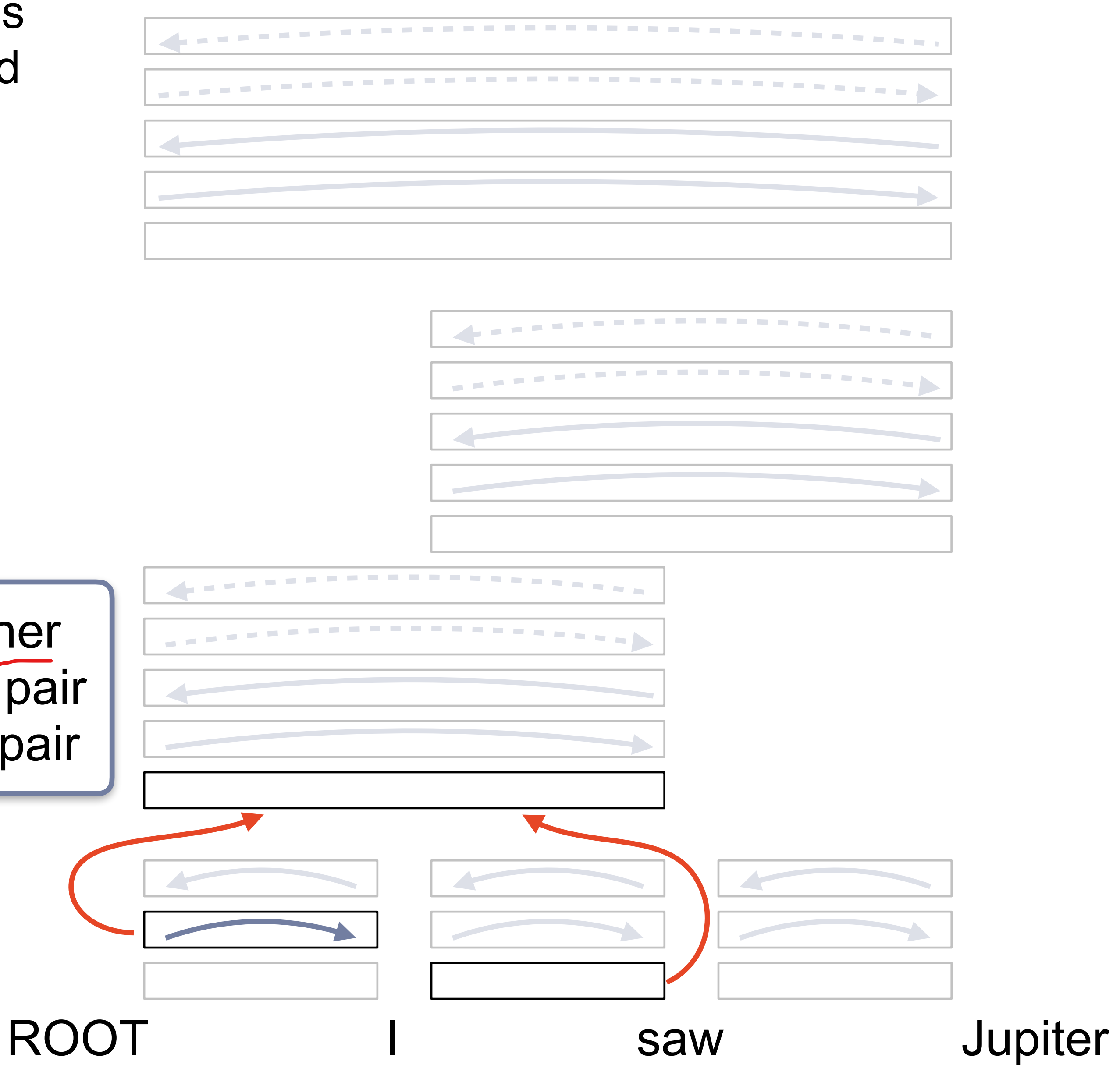
We use the items and rules to build up the parse

Keep the higher scoring of this pair and the other pair

Apply combination rules



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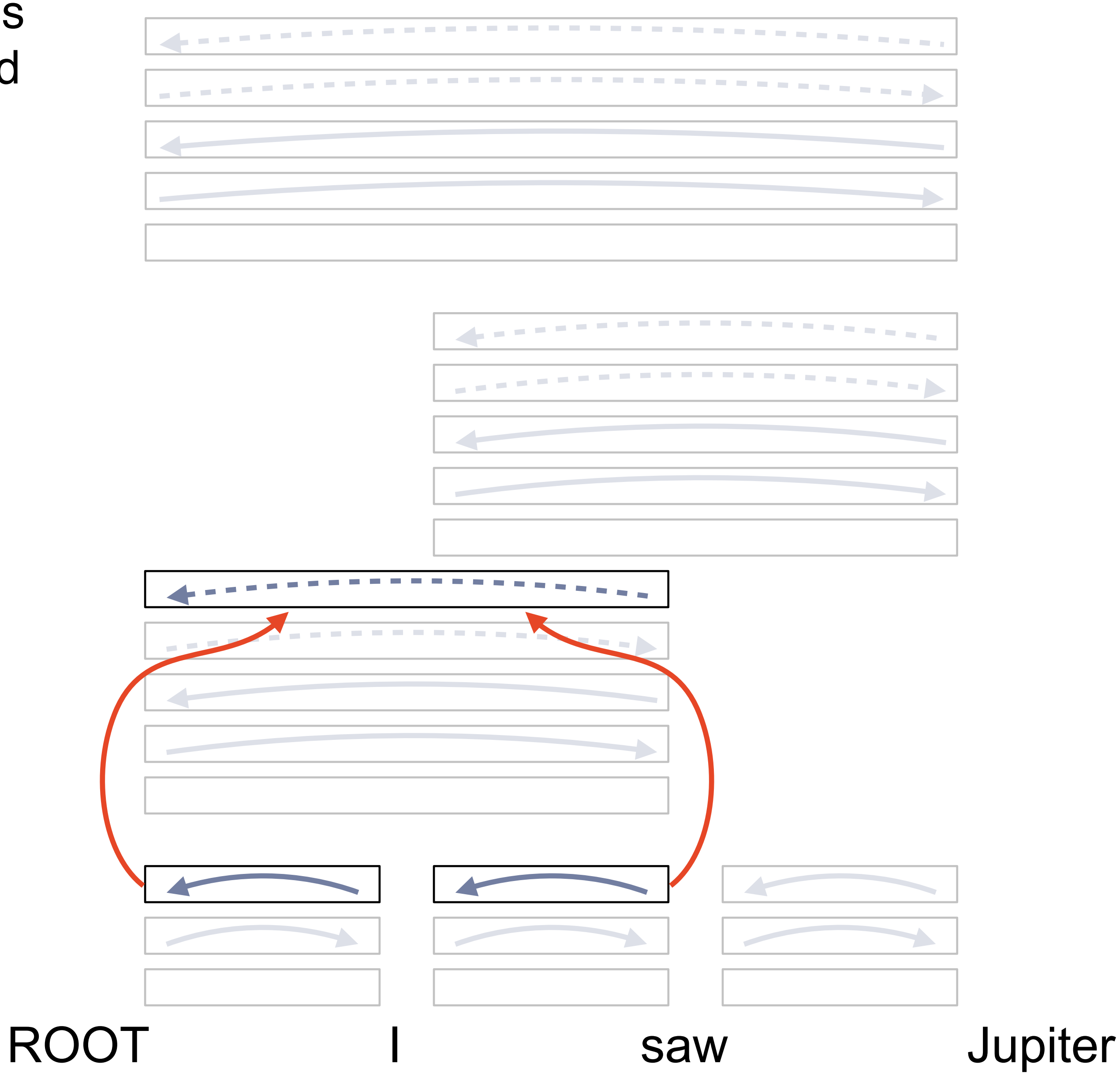

Apply combination rules

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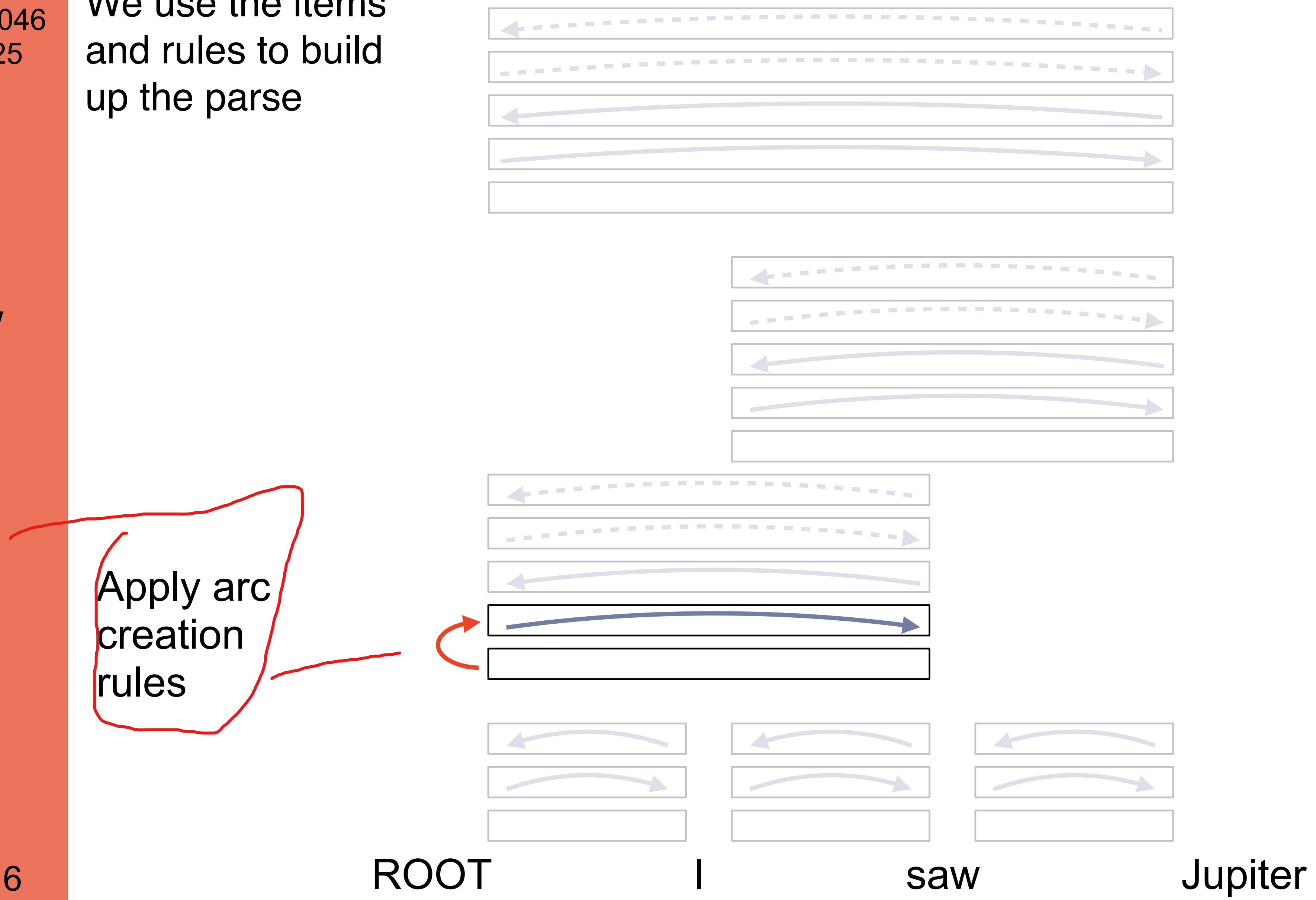

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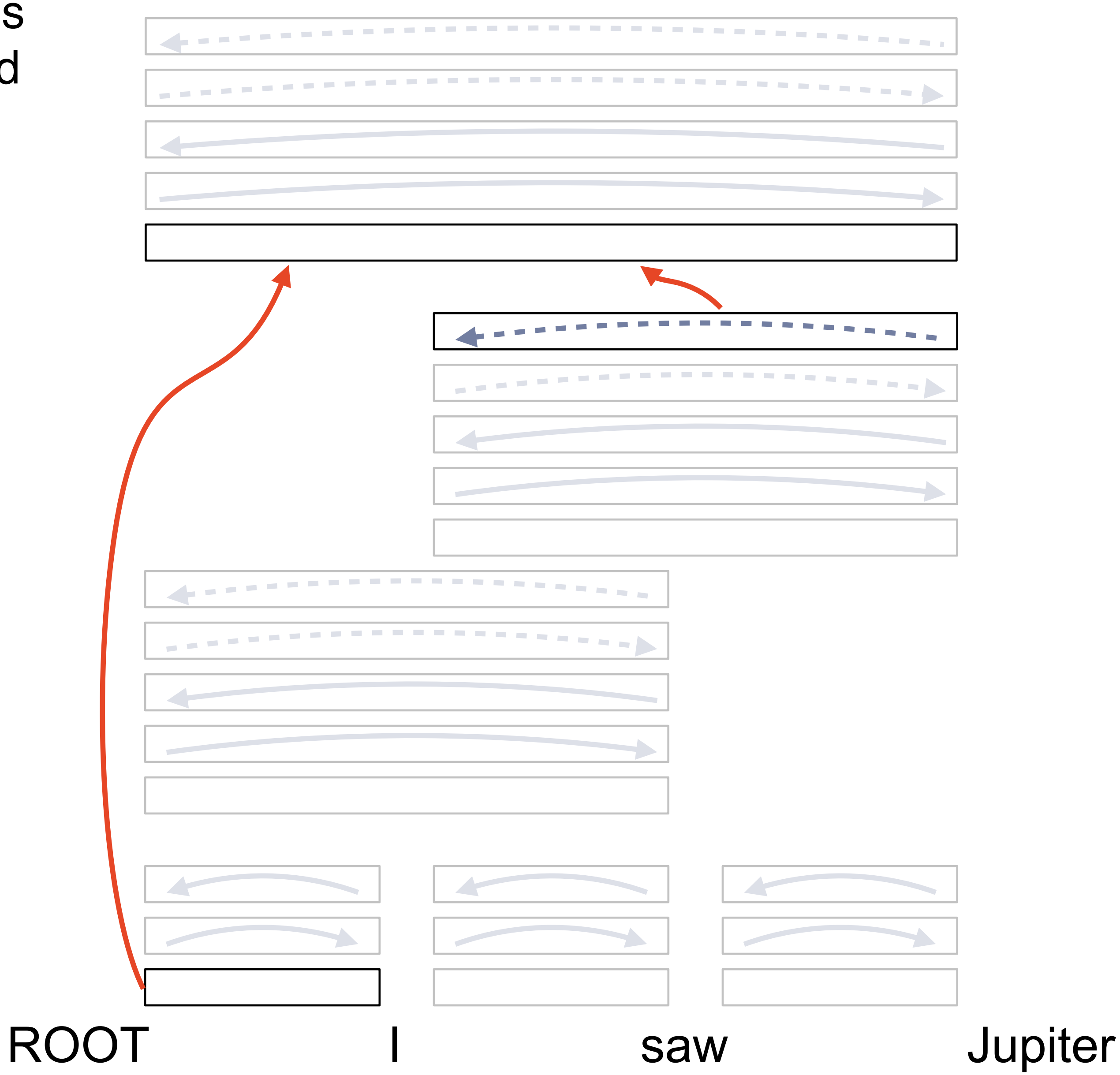

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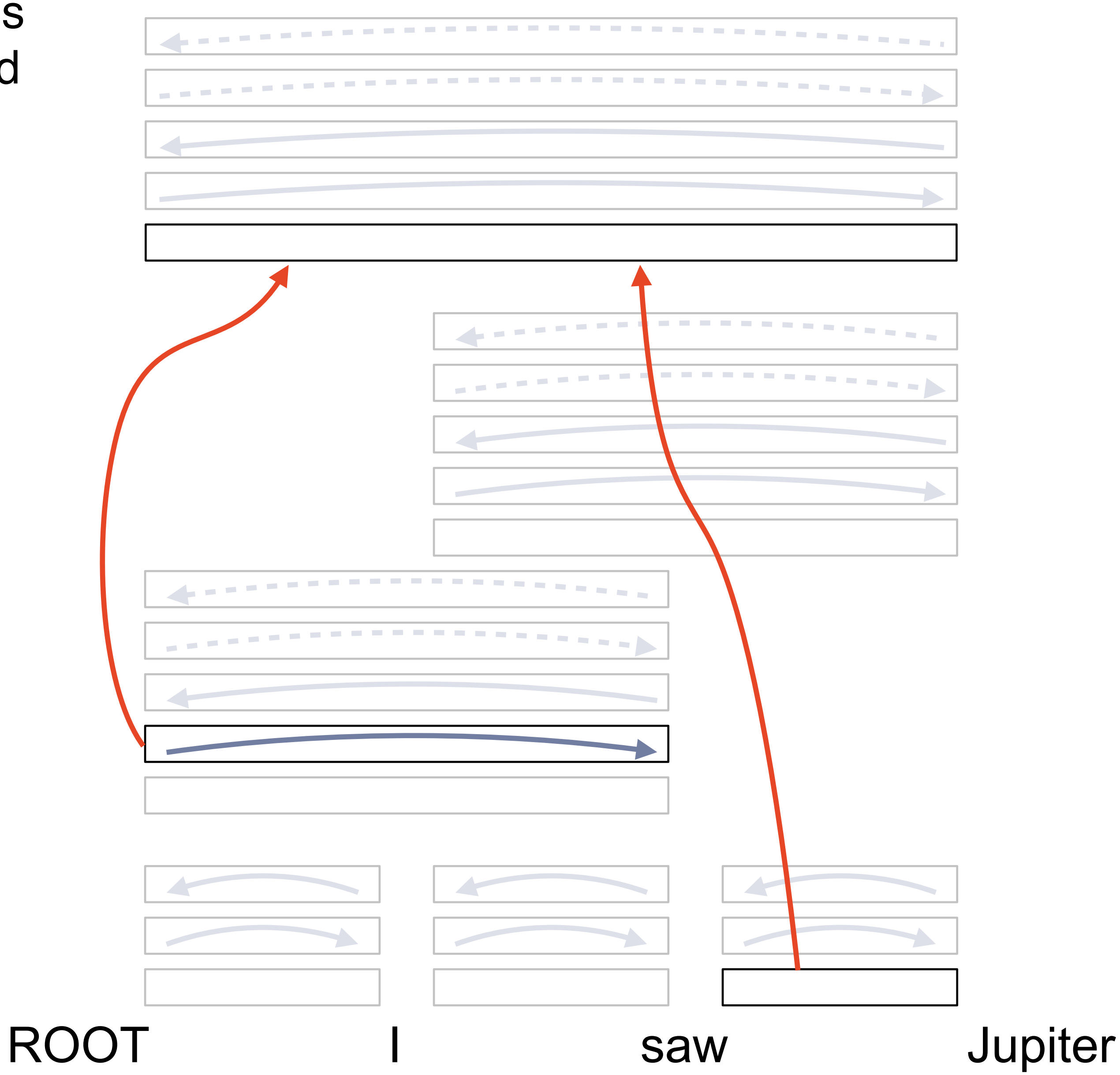

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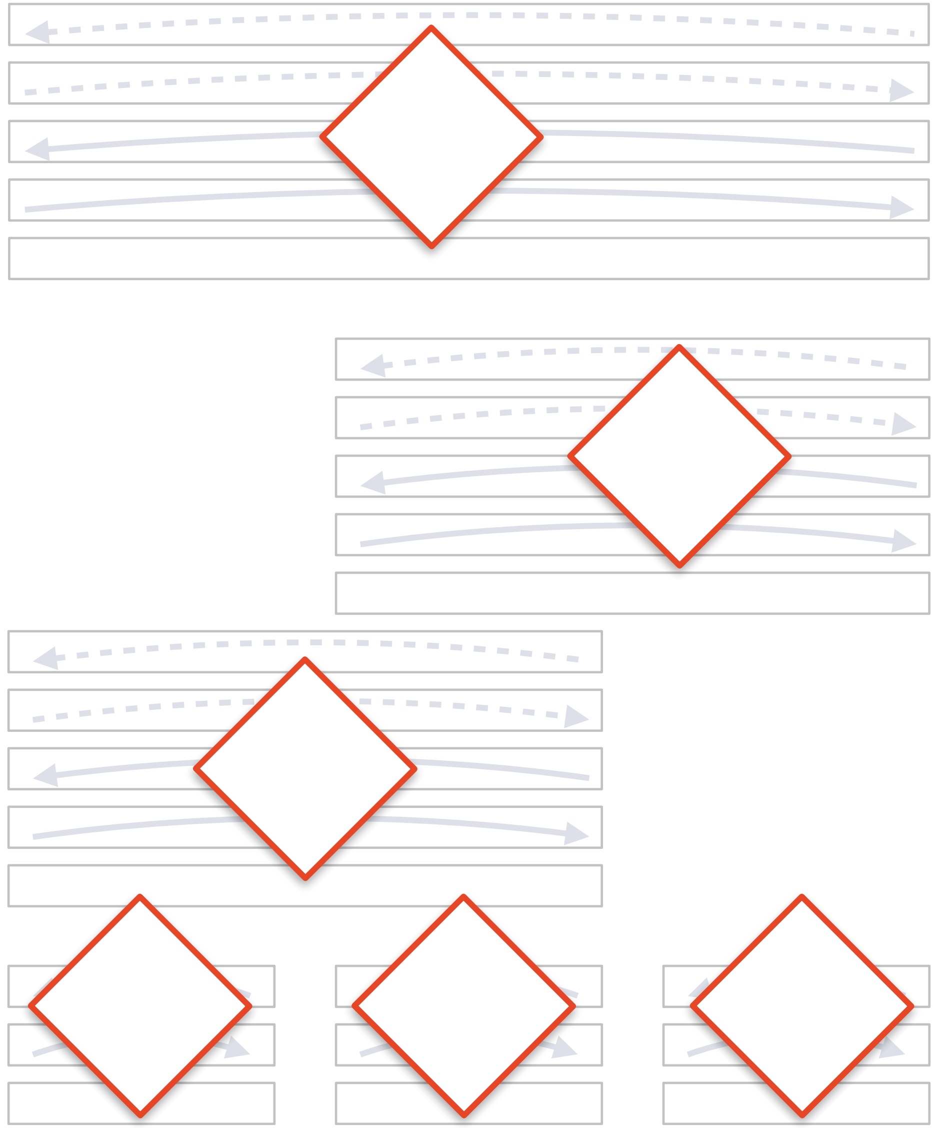
General idea: Consider each way to form each item, store the best and how you got it



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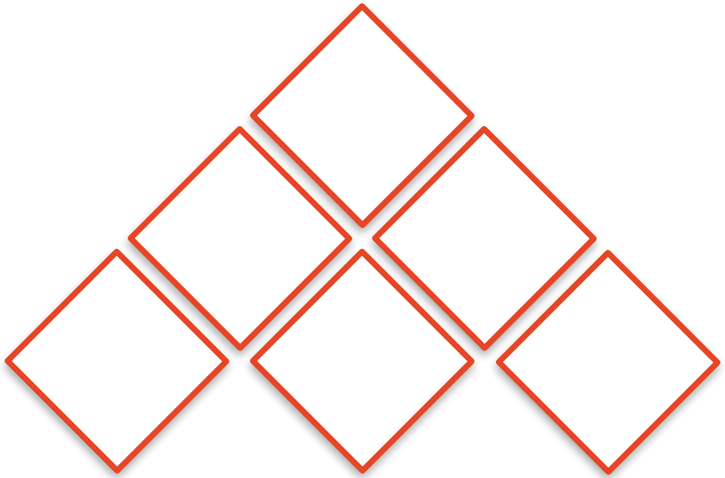

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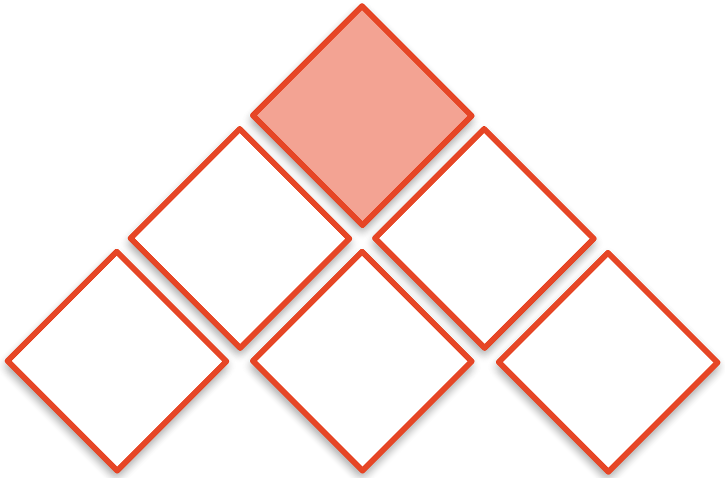

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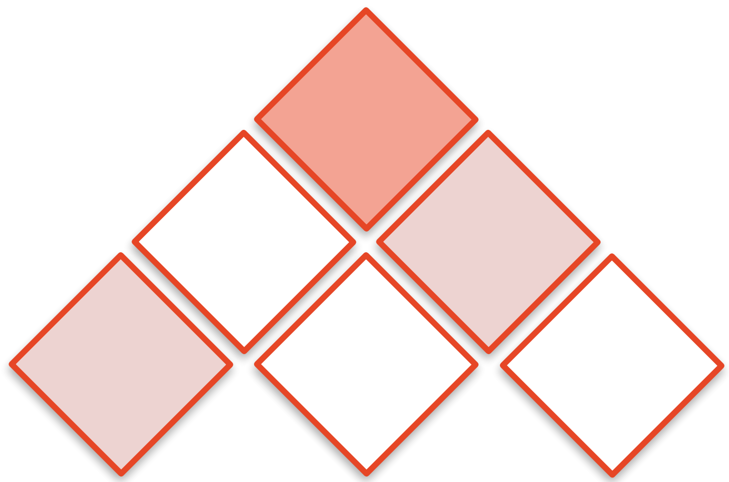

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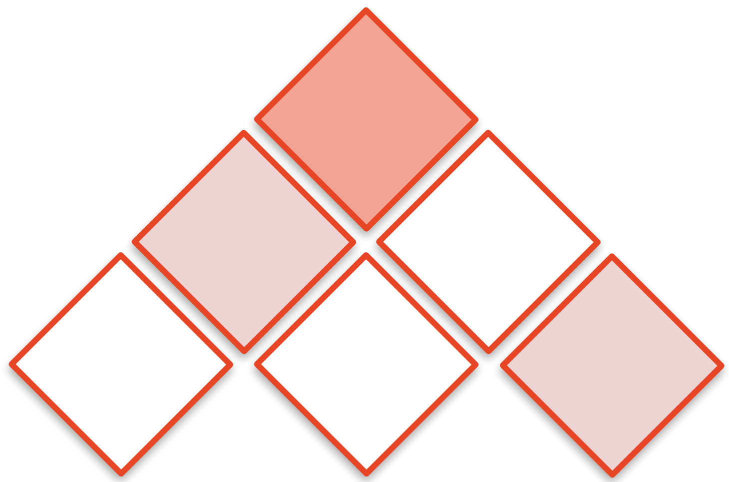

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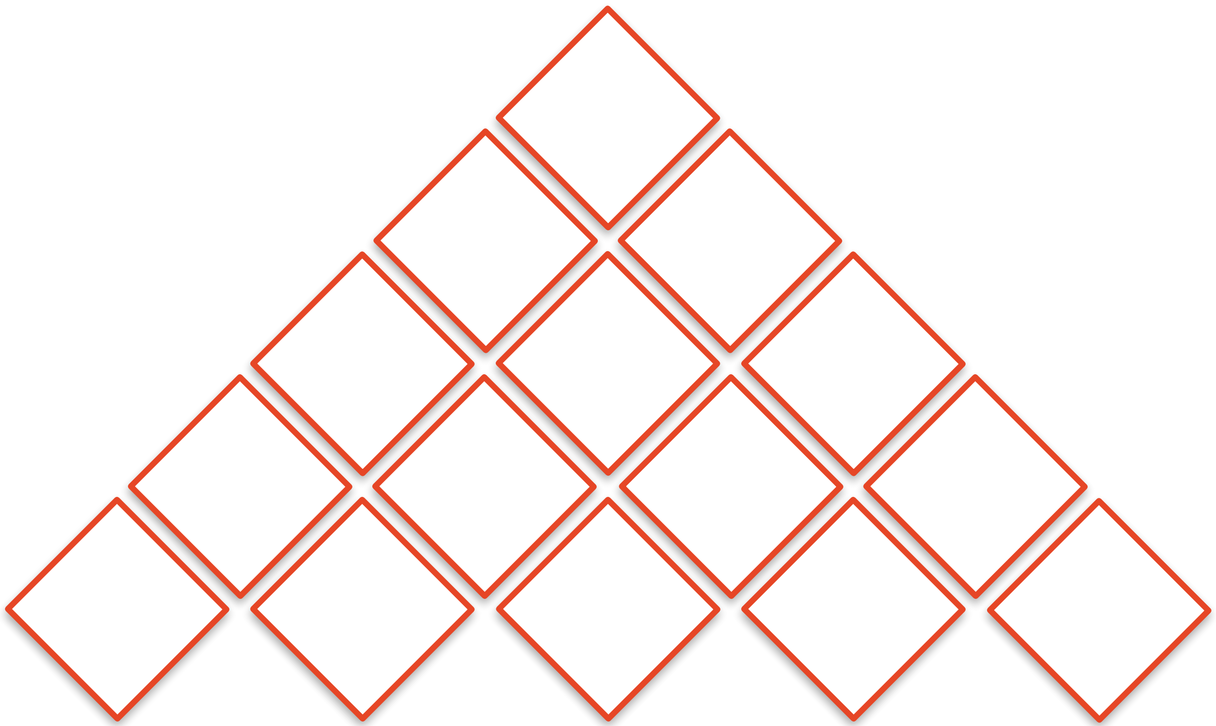

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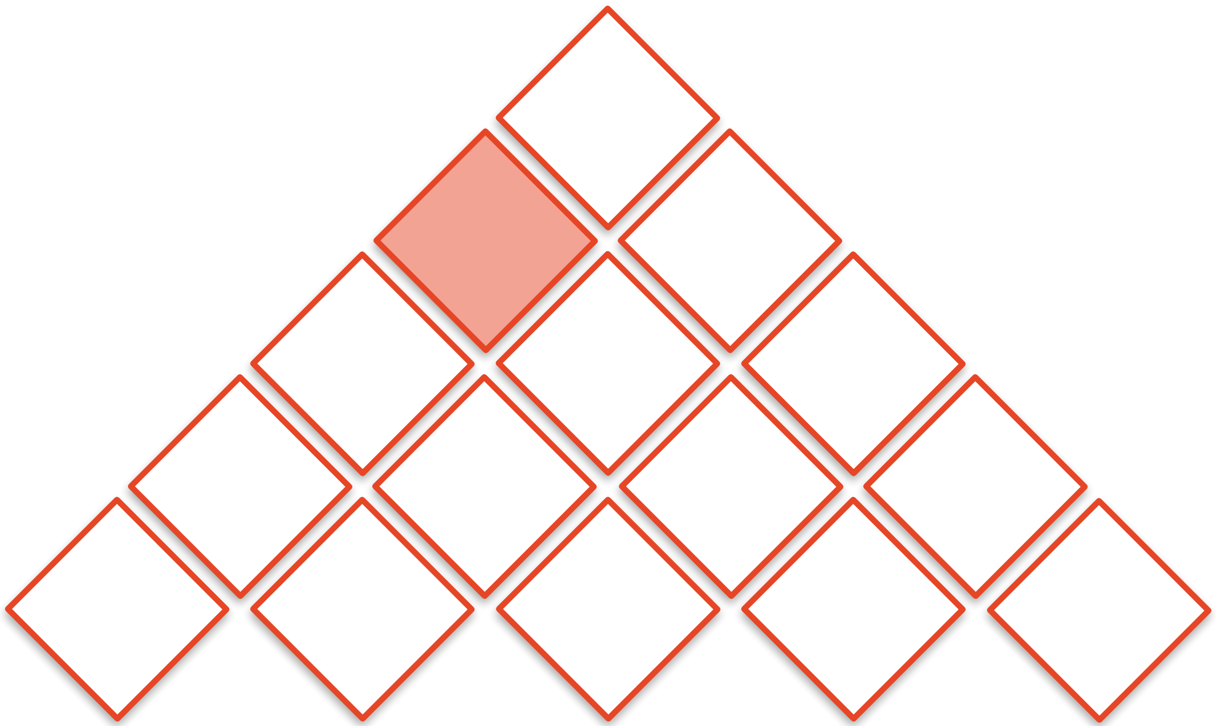

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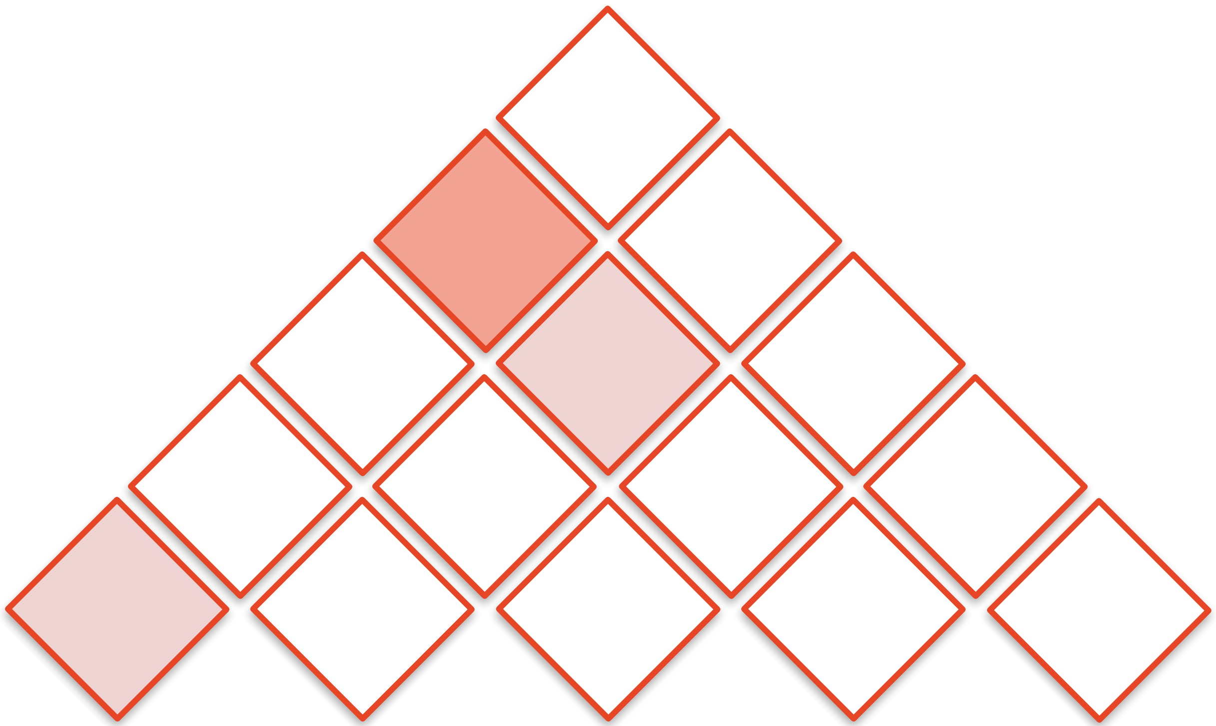

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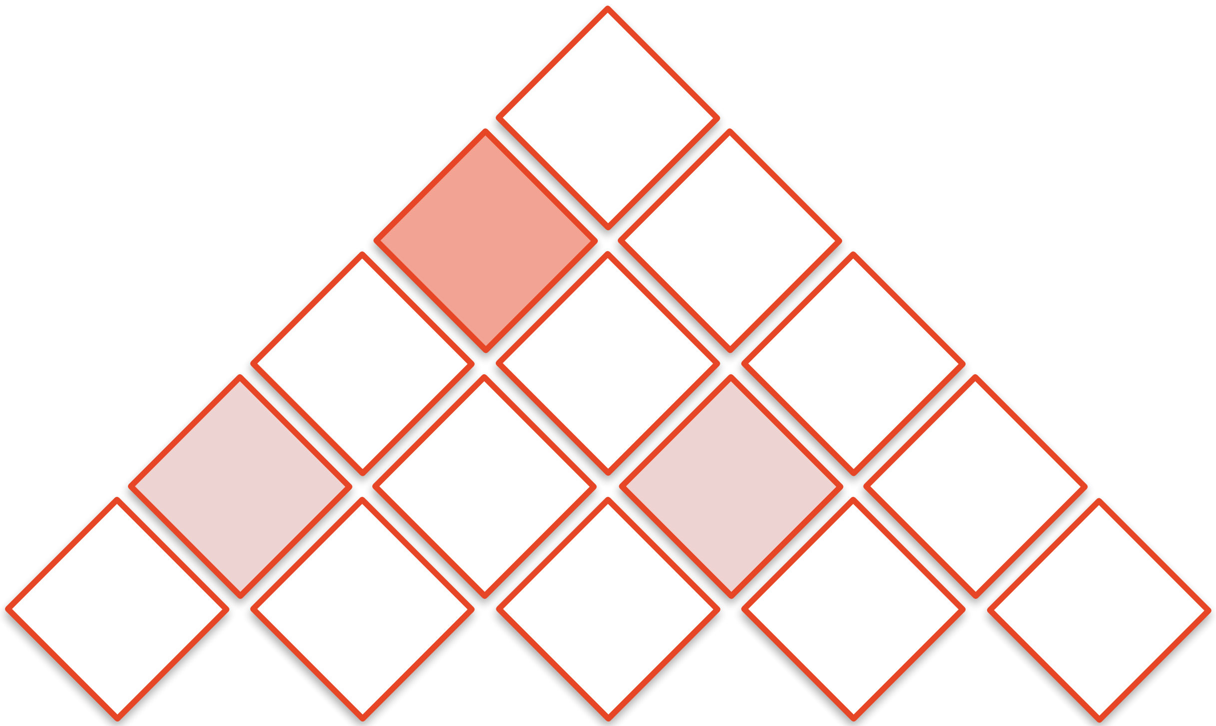

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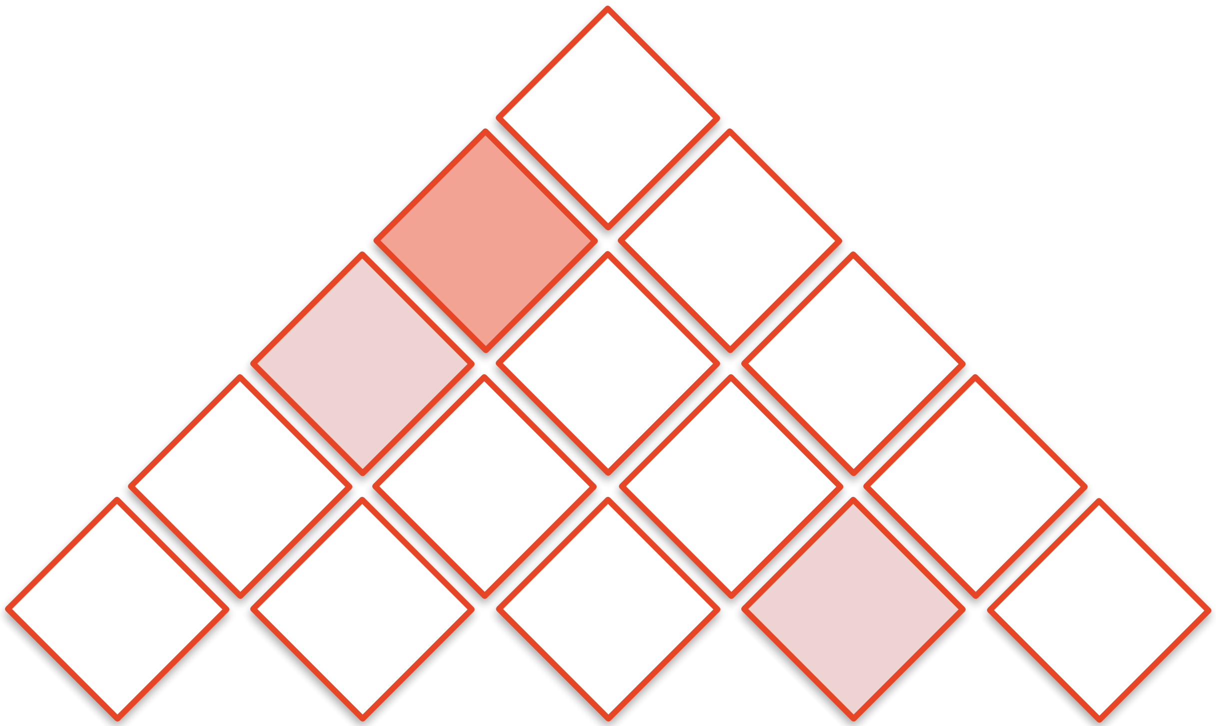

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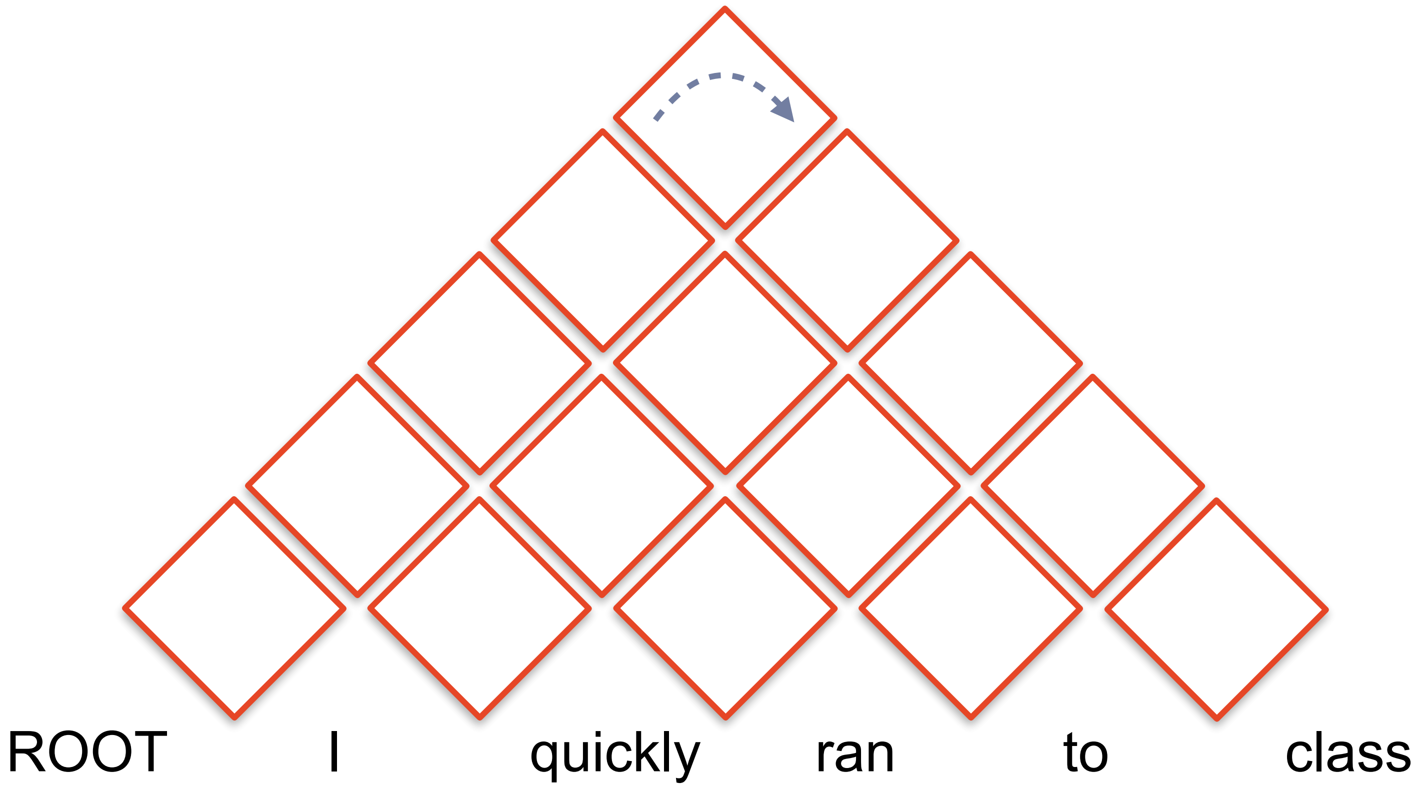
At the end, start at the top and work downwards to get the parse



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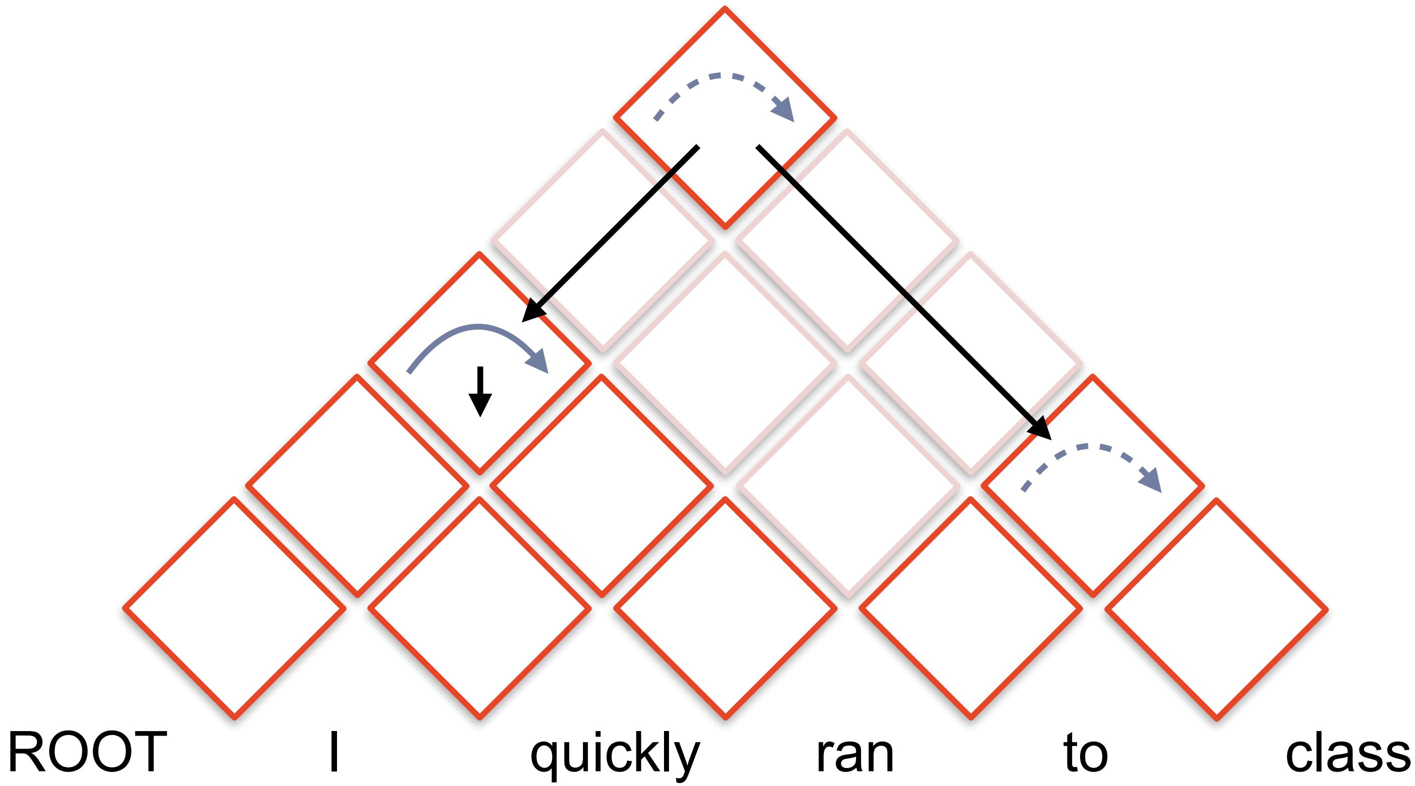

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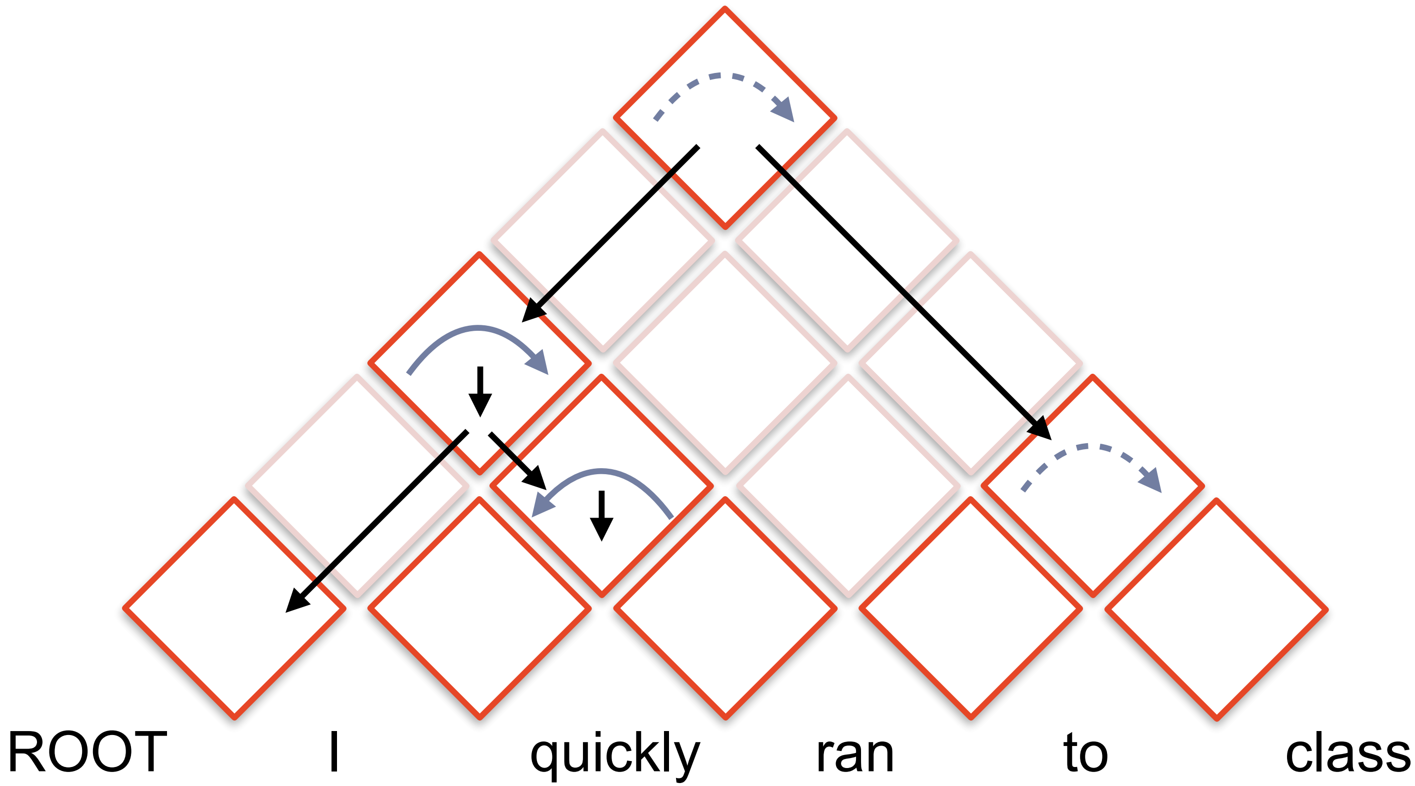

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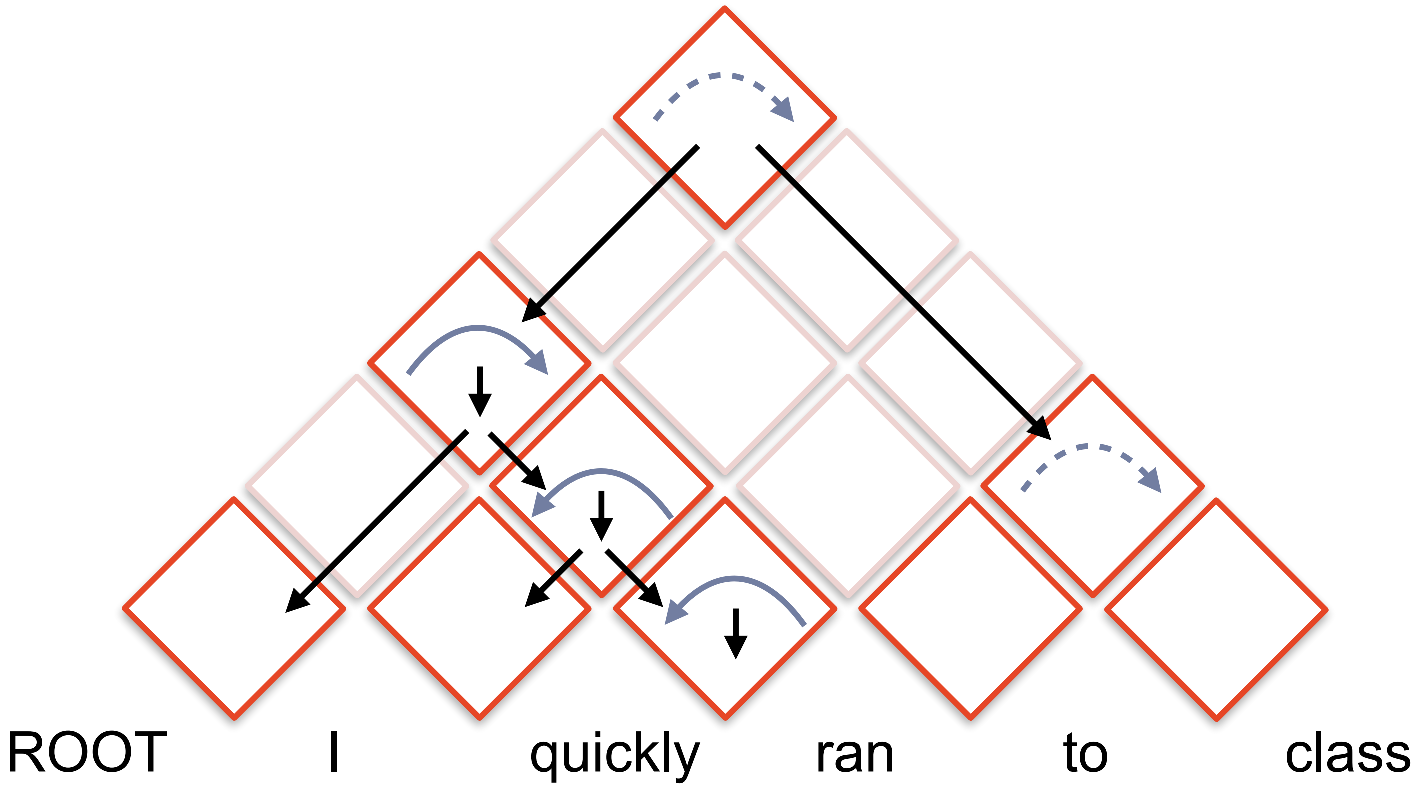

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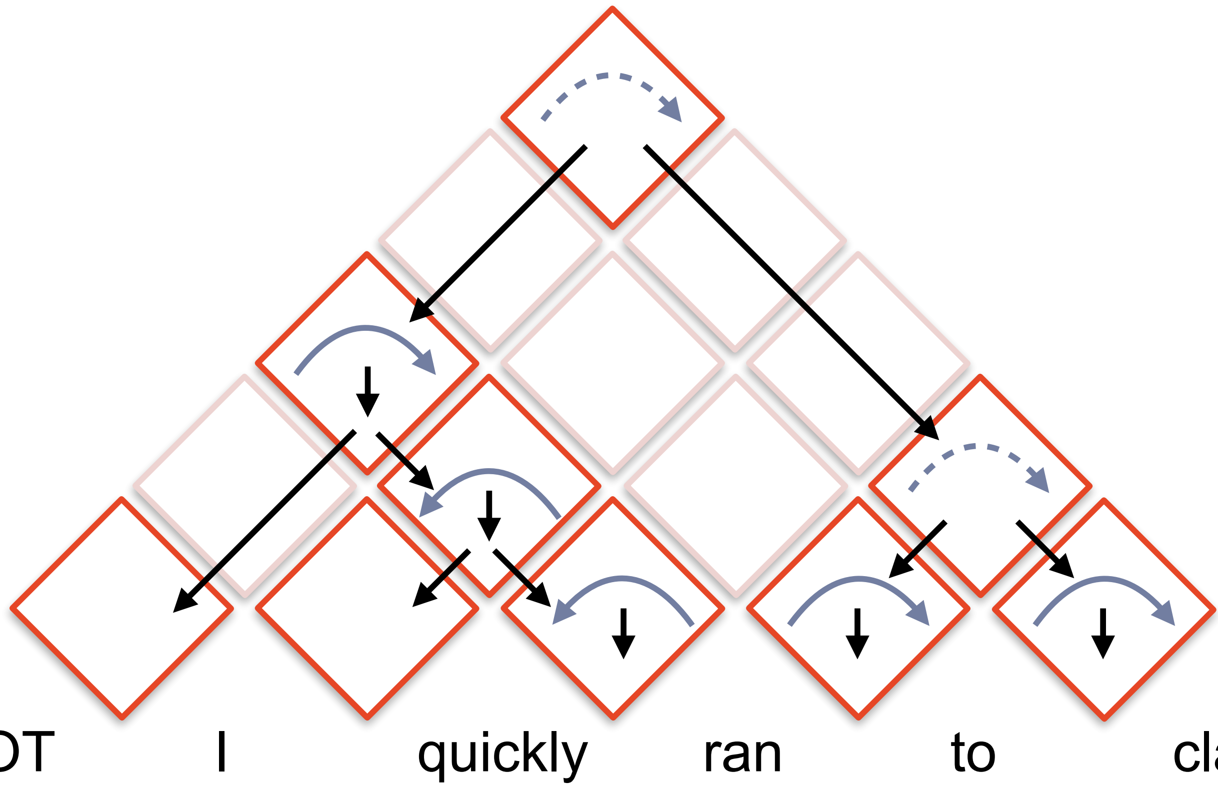

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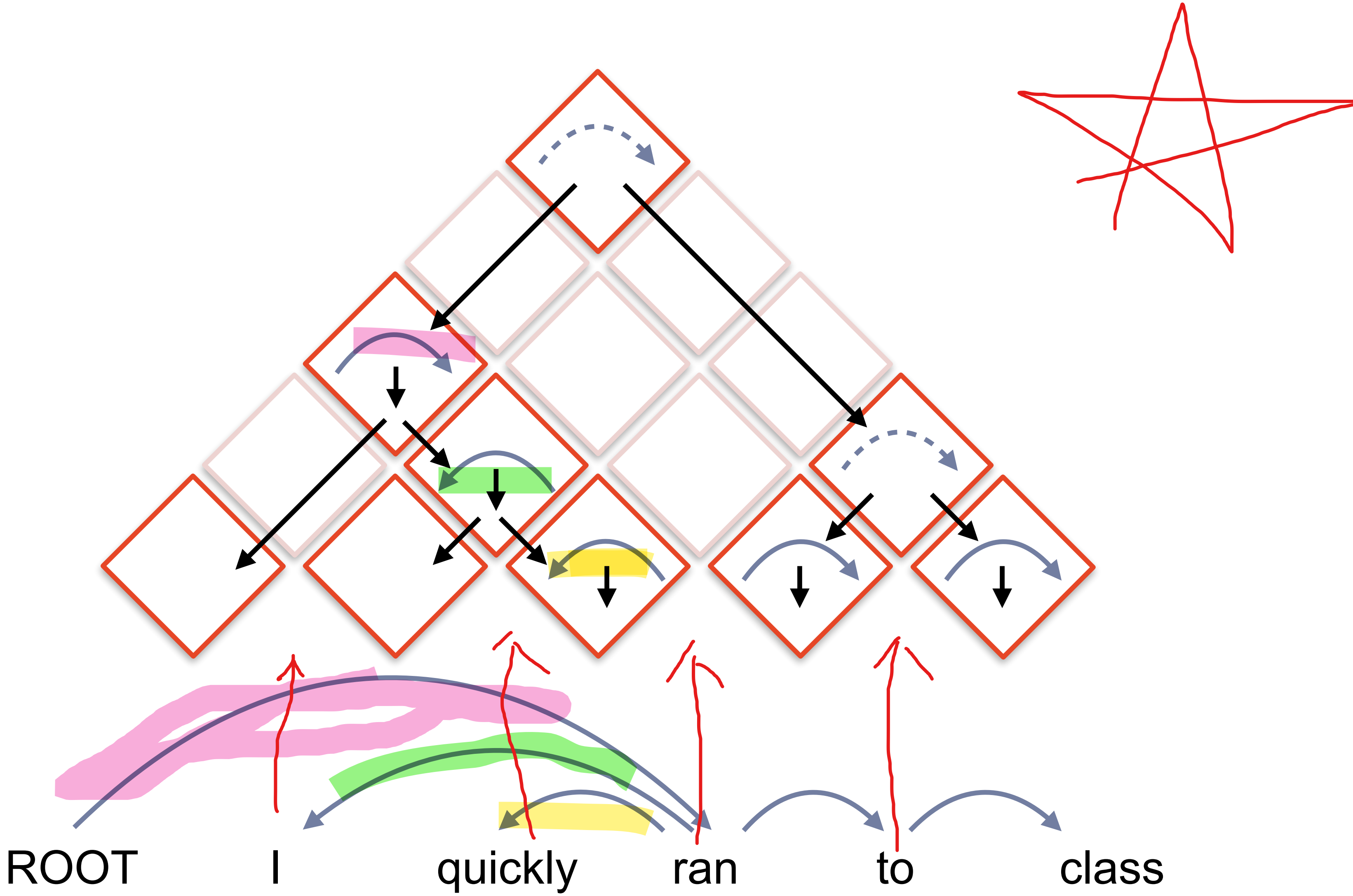
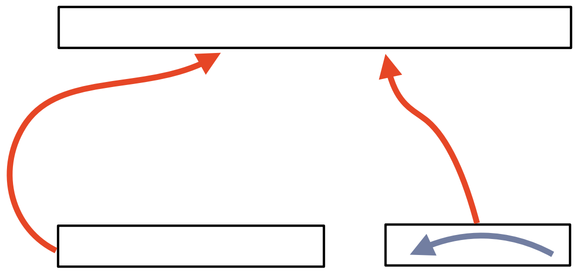


Algorithm in pseudocode

Called the CKY algorithm
..or CYK algorithm

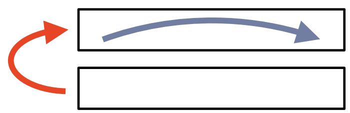
```
Create storage for best options for each span
and item type

Insert initial items
For each possible span length
    For each possible span start
        For each possible item type
            Best = None
            For each possible split point
                For each rule
                    Get the score for this
                    combination and update best
            Record the best
        Get the scores for adding an arc to the
        empty items and record them
```

Time complexity is $O(|rules_{comb}||words|^3 + |rules_{arc}||words|^2)$



Combinations:

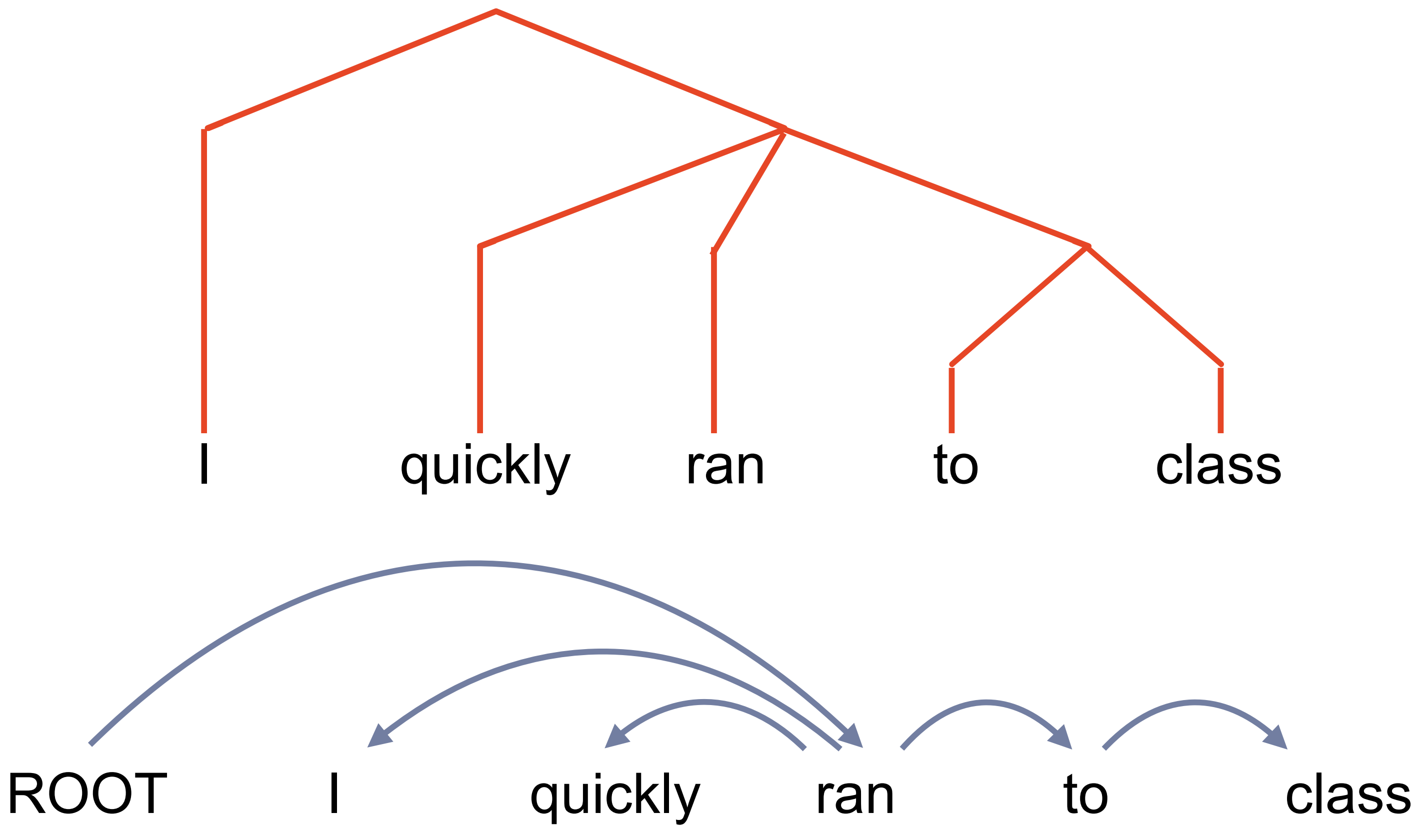
Each start point	$O(\|words\|)$
Each length	$O(\|words\|)$
Each split point	$O(\|words\|)$
Each rule	$O(\|rules_{comb}\|)$



Arc creation:

Each start point	$O(\|words\|)$
Each length	$O(\|words\|)$
Each rule	$O(\|rules_{arc}\|)$

Dependencies are one representation, constituency parses are another



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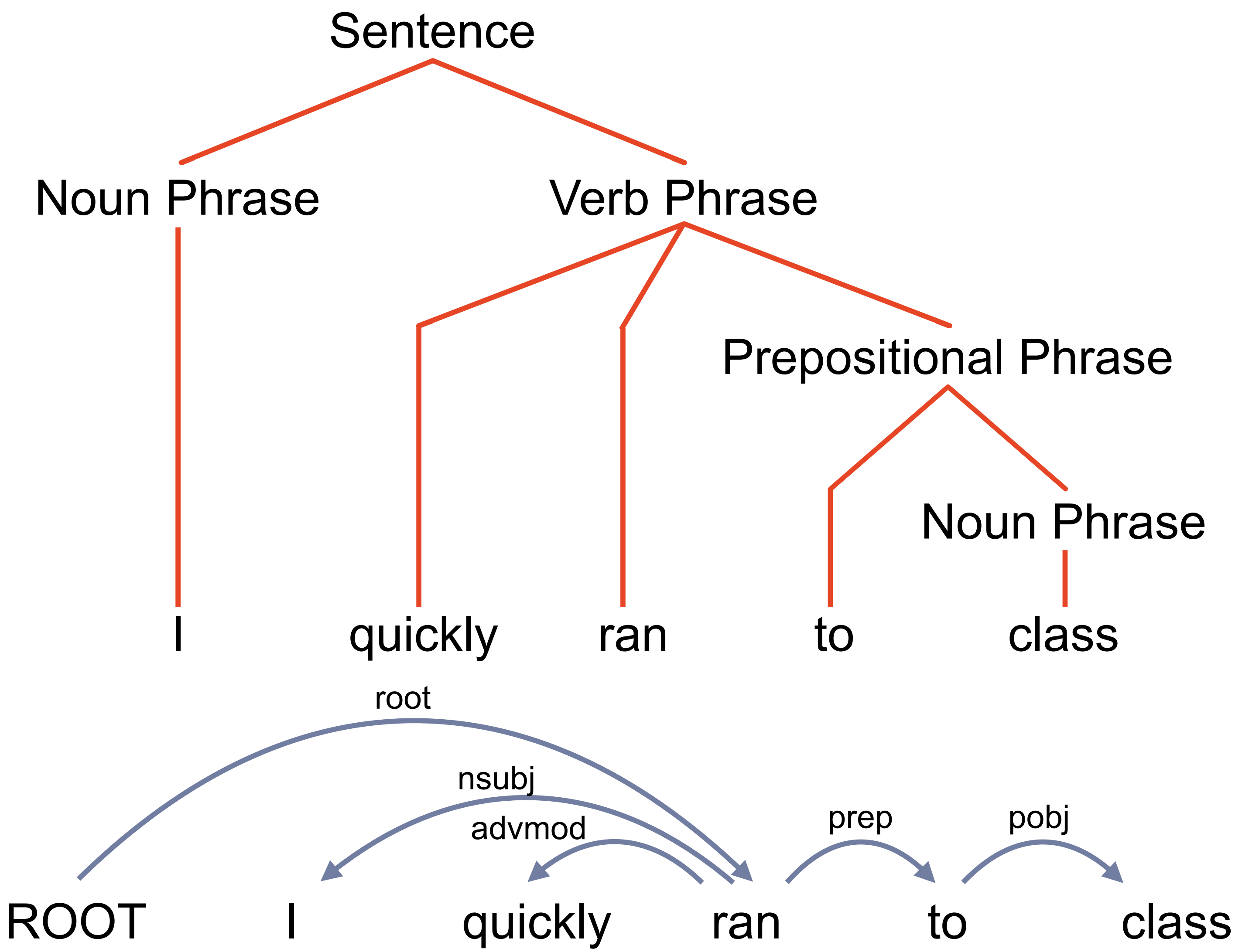

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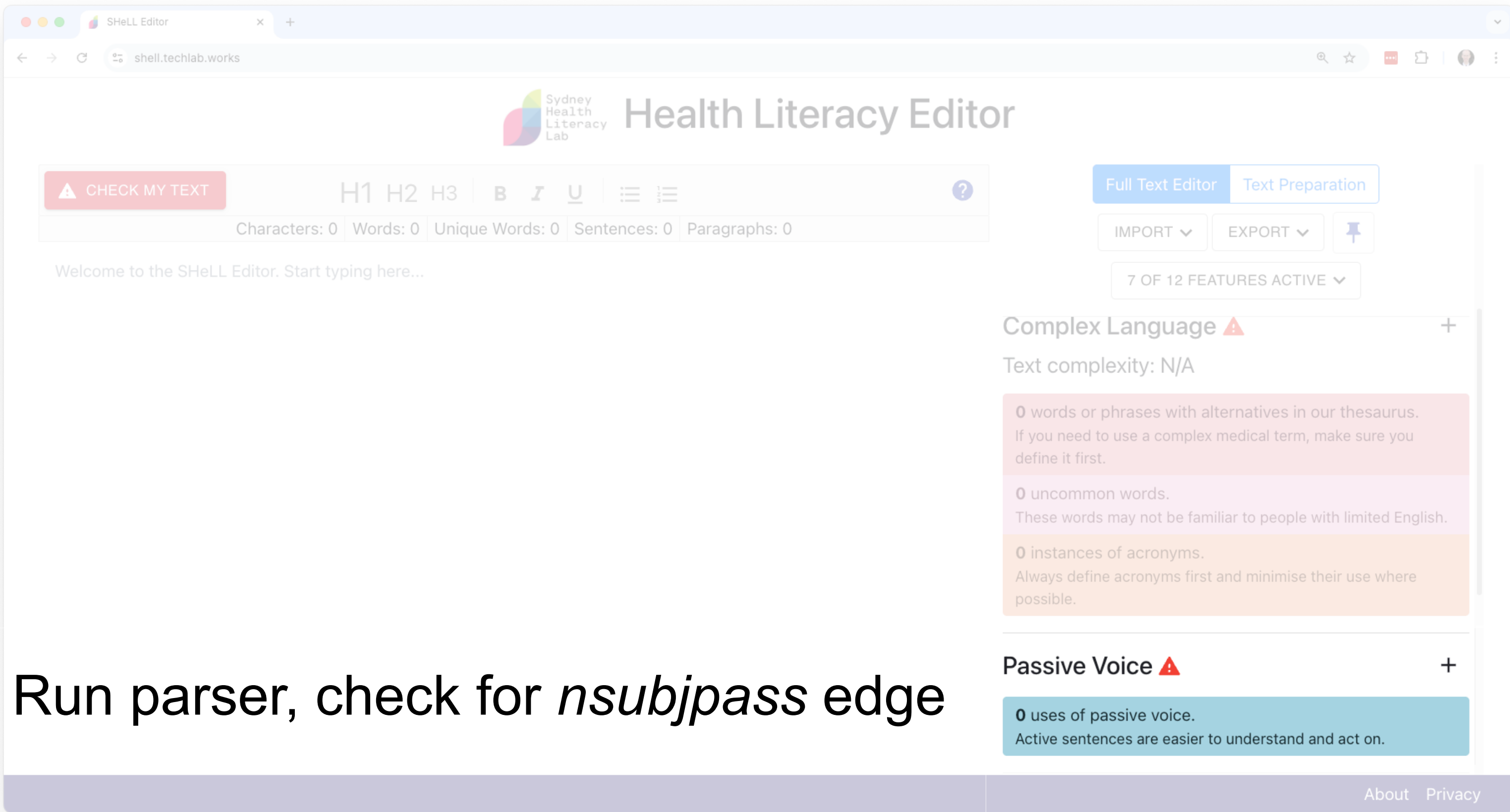
Why is this still relevant in the age of LLMs?

Usage

1. Occasionally, this is what you need



Run parser, check for *nsubjpass* edge

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Why is this still relevant in the age of LLMs?

2. You can use parsing as part of a system

We propose a new representation and algorithm for a class of graph structures that is flexible enough to cover almost all treebank structures, while still admitting efficient learning and inference

Why is this still relevant in the age of LLMs?

2. You can use parsing as part of a system

We propose a new representation and algorithm for a class of graph structures that is flexible enough to cover almost all treebank structures, while still admitting efficient learning and inference.

Limit parts of text to query LLM with based on the parse, e.g., don't cut in the middle of an arc

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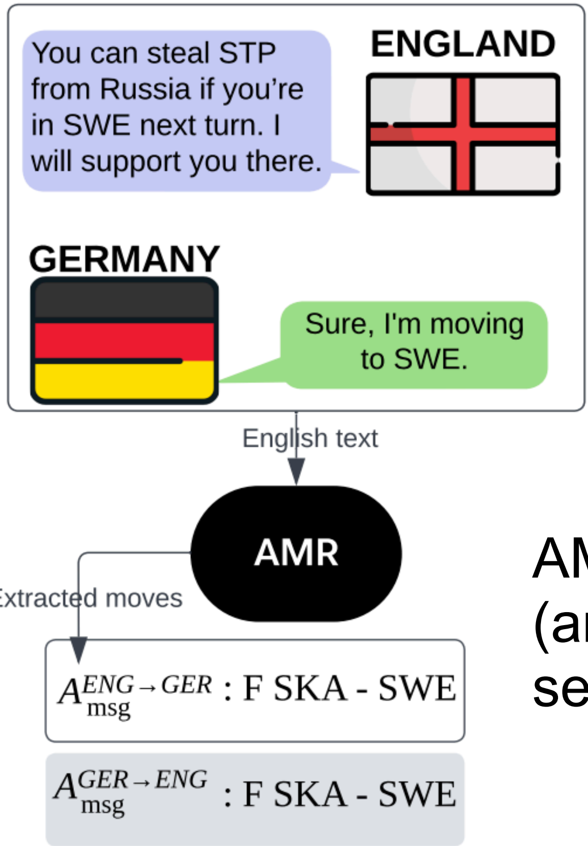
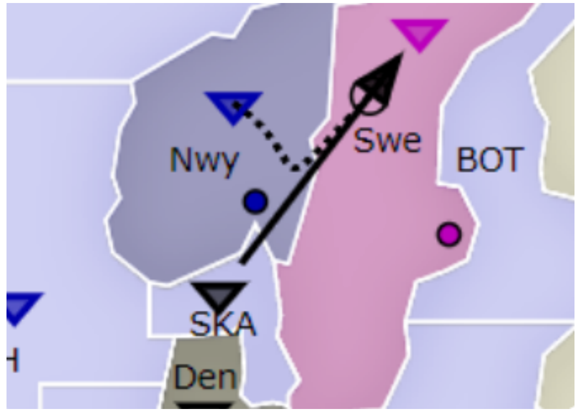
Why is this still relevant in the age of LLMs?

3. LLMs are still bad at some things





AMR = Abstract Meaning Representation (another type of parsing, focused on semantics rather than syntax)

3 minute Break - stretch and visit Menti

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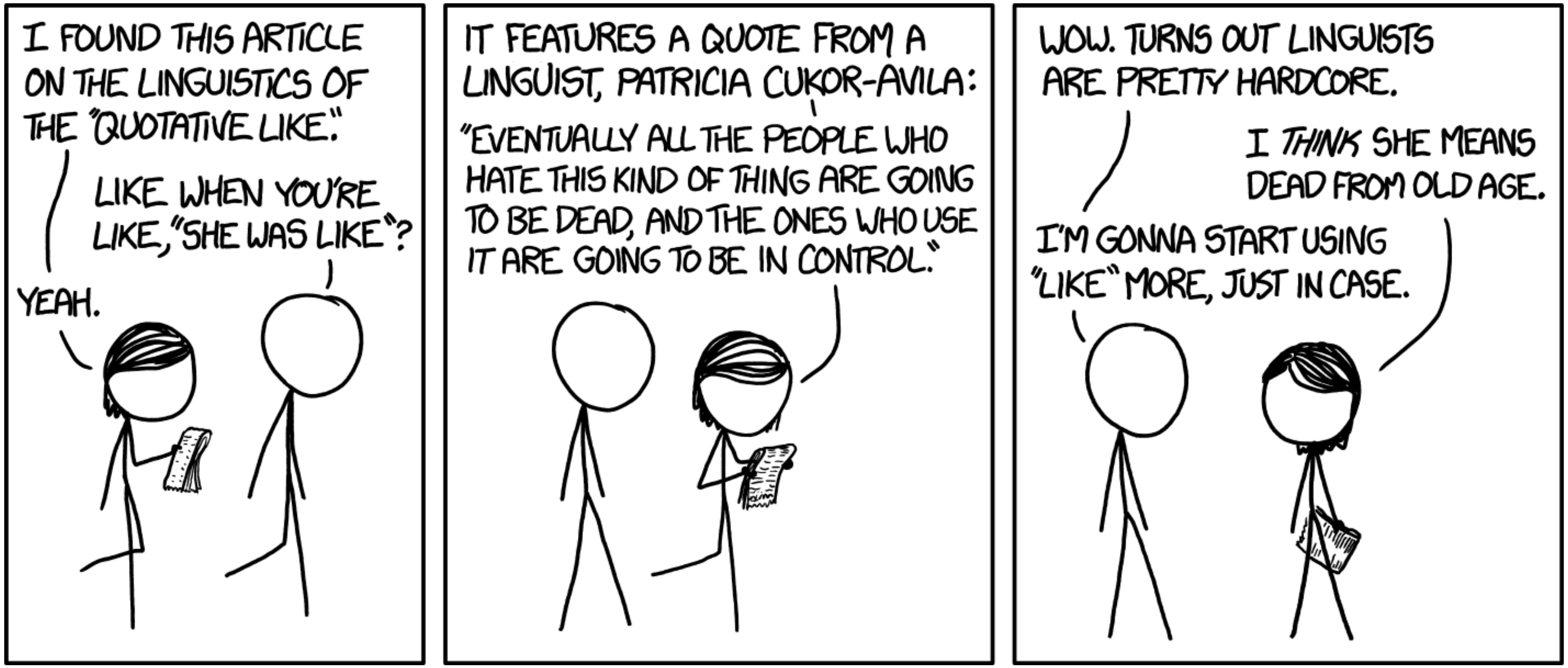
Quotative Like



[God was like, "Let there be light," and there was light.]

Source: https://xkcd.com/1483/

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Coreference

References are when entities are mentioned in text

<ins>Victoria Chen</ins>, CFO of <ins>Megabucks Banking</ins>, saw <ins>her pay</ins> jump to $2.3 million, as the 38-year-old became the company's president. It is widely known that she came to Megabucks from rival <ins>Lotsabucks</ins>.

Example text is from the J+M textbook, chapter 23

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Coreference is identifying which mentions refer to the same entity

Victoria Chen

Megabucks Banking

Lotsabucks

her pay

Victoria Chen, CFO of Megabucks Banking, saw her pay jump to $2.3 million, as the 38-year-old became the company's president. It is widely known that she came to Megabucks from rival Lotsabucks.

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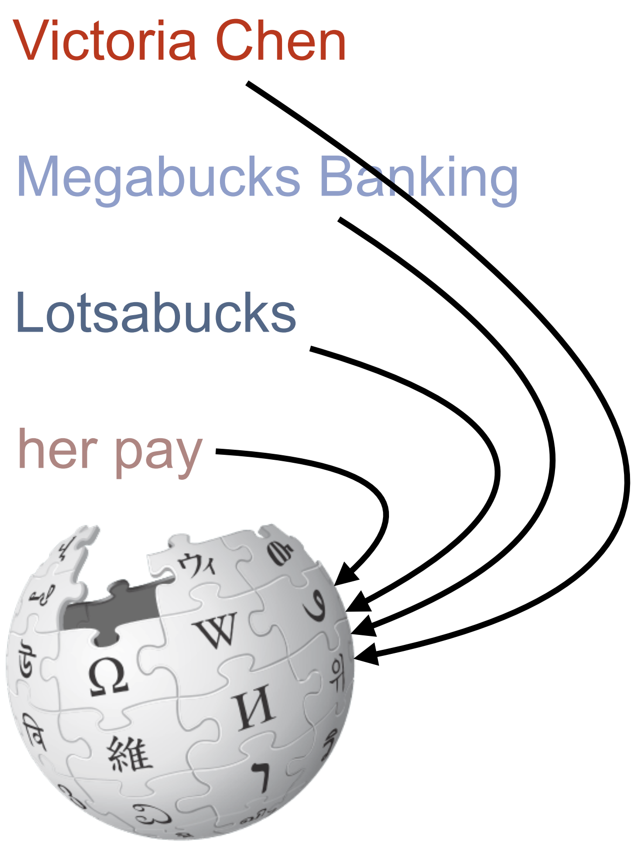
Entity Linking / Wikification is a related task that links each entity to an external knowledge base



Victoria Chen, CFO of Megabucks Banking, saw her pay jump to $2.3 million, as the 38-year-old became the company’s president. It is widely known that she came to Megabucks from rival Lotsabucks.

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The search space is huge!

Possible references:
|words| * |words|

Possible sets:
All ways to cluster
all references

Victoria Chen, CFO of Megabucks Banking, saw her pay jump to $2.3 million, as the 38-year-old became the company's president. It is widely known that she came to Megabucks from rival Lotsabucks.

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First idea for simplification: do mention detection and filtering first

Possible references:
|words| * |words|

Victoria
Victoria Chen
Victoria Chen ,
Victoria Chen , CFO
Victoria Chen , CFO of
Victoria Chen , CFO of Megabucks
Victoria Chen , CFO of Megabucks Banking
Victoria Chen , CFO of Megabucks Banking ,
Victoria Chen , CFO of Megabucks Banking , saw
Victoria Chen , CFO of Megabucks Banking , saw her

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First idea for simplification: do mention detection and filtering first

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Victoria Chen
~~Victoria Chen ,~~
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~~Victoria Chen , CFO of Megabucks~~
~~Victoria Chen , CFO of Megabucks Banking~~
~~Victoria Chen , CFO of Megabucks Banking ,~~
~~Victoria Chen , CFO of Megabucks Banking , saw~~
~~Victoria Chen , CFO of Megabucks Banking , saw her~~

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Second idea for simplification: Link pairs of mentions

Just find the best previous mention for this mention to be coreferent with

Victoria Chen, CFO of Megabucks Banking, saw her pay jump to $2.3 million, as the 38-year-old became the company's president. It is widely known that she came to Megabucks from rival Lotsabucks.

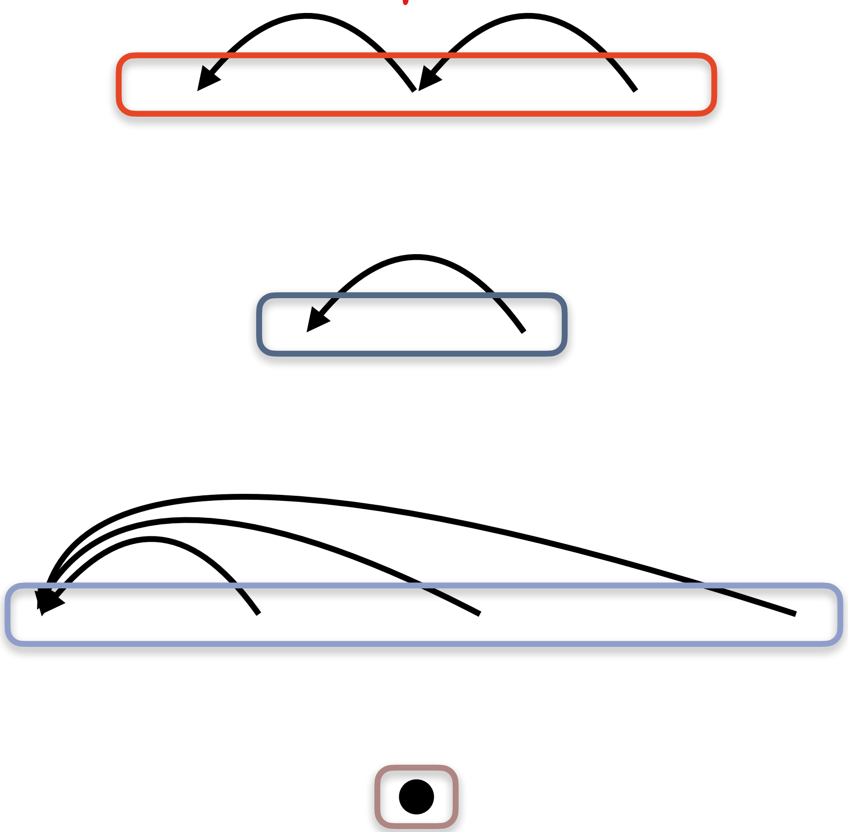
Second idea for simplification: Link pairs of mentions

Just find the best previous mention for this mention to be coreferent with

Victoria Chen, CFO of Megabucks Banking, saw her pay jump to $2.3 million, as the 38-year-old became the company's president. It is widely known that she came to Megabucks from rival Lotsabucks.

Third idea for simplification: Find the transitive closure

Cluster are separate i.e. no arrow toward other cluster



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But what about fancy inference algorithms?

why we not always use llm

Sometimes the simple idea ***does*** work!

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Workshop preview - Keras and Tensorflow

Pre-Work	Confirm you can run the notebook on your own machine / a web service! Read the initial sections
In Workshop	LSTM variations GPT-2 text generation

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Muddy Card

Open shortly, closes at 7:05pm

https://saipll.shinyapps.io/student-interface/

If you do not wish to participate in the study, use the Ed form instead

Go to Ed → Lessons → Muddy Cards Lecture 5