

# Wrap-Up: Unsupervised Learning + Summary

LING 571 — Deep Processing Methods in NLP

December 4, 2019

Shane Steinert-Threlkeld

# A Roadblock to Deep Processing

- Deep processing of natural language data helps with:
  - Information retrieval
  - QA
  - WSD
  - Conversational AI
  - ...
- But....

# Developing Deep Processing Systems

- Building a deep processing system requires lots of annotated data
  - For evaluation
  - For *training* an ML system

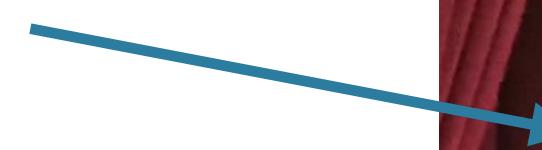
# A roadblock

- The following are cheap:
  - Compute
  - Text [the web!]
- The following are expensive:
  - Human hours
    - Programmers
    - Data annotators

# Un-/Semi-supervised Learning in NLP

# Can we leverage the cheap resources?

Yann LeCun



# Main Idea

- Leverage the huge amounts of text to learn useful representations
- “Fine tune” on a much smaller amount of task-specific data
  - a.k.a. transfer learning

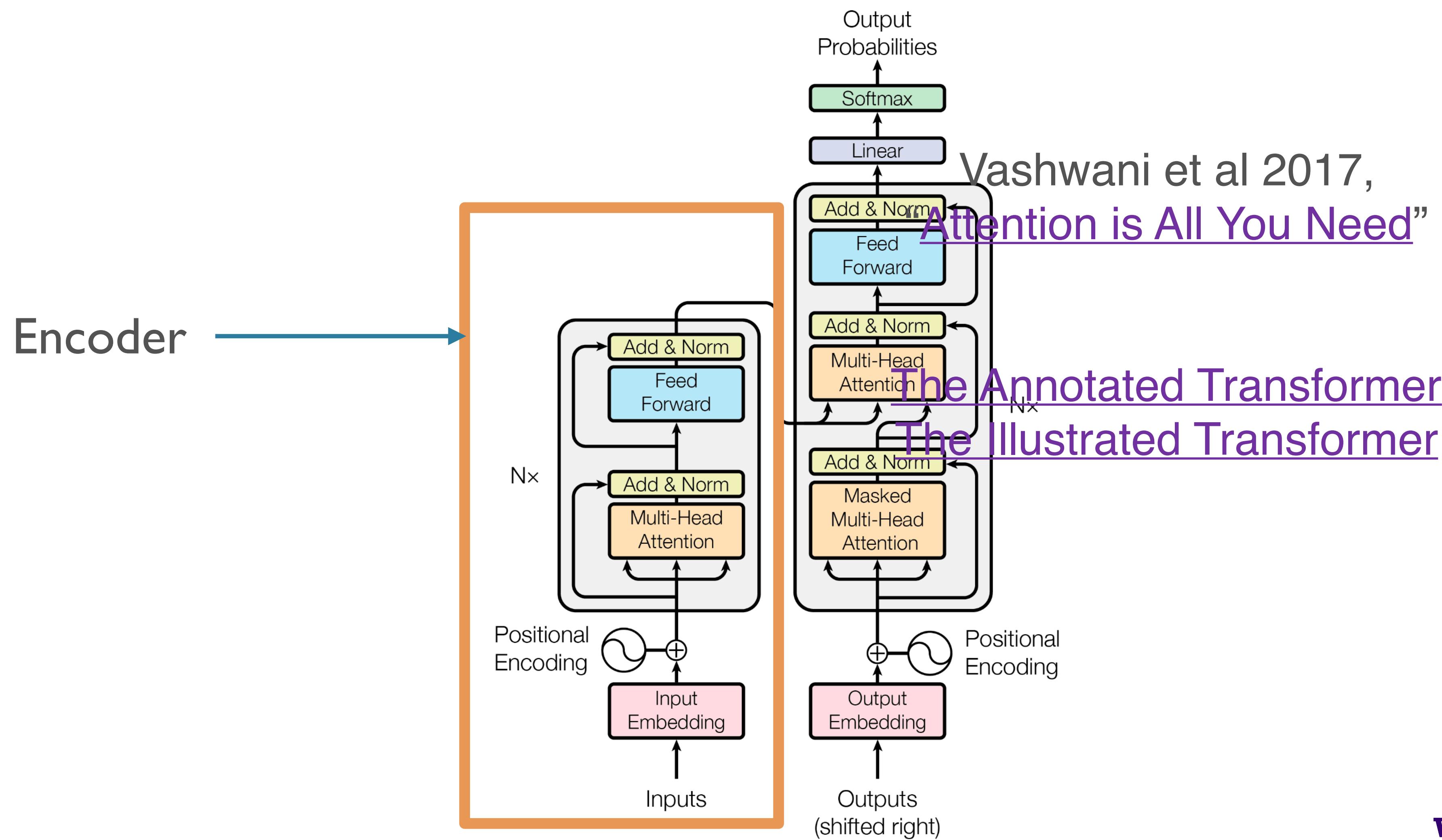


# BERT

Bidirectional Encoder Representations from Transformers

Devlin et al 2018

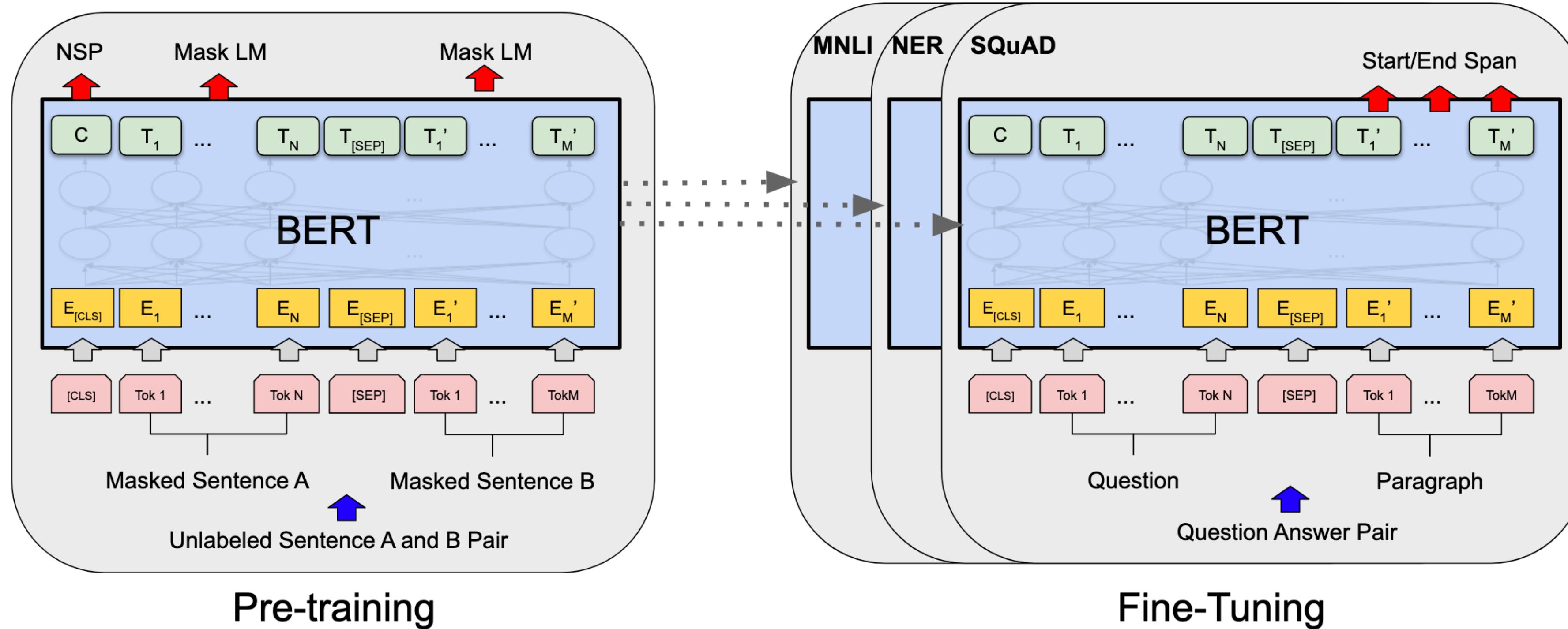
# Transformers [+ Encoder]



# Bidirectional: Masked Language Modeling

- Main training task: *masked language modeling* (aka cloze task)
  - Raw text: “Seattle is the capital of Washington and is the home of UW.”
  - 15% of tokens are masked\* (\*some subtleties), e.g.:
  - Model input:
    - “Seattle is the [MASK] of Washington and [MASK] the home of UW.”
    - Task: predict the tokens in the [MASK] positions.
  - [Also trained with Next Sentence Prediction: given two sentences, did the second follow the first in the text?]

# Fine Tuning



# Initial Results

System	MNLI-(m/mm) 392k	QQP 363k	QNLI 108k	SST-2 67k	CoLA 8.5k	STS-B 5.7k	MRPC 3.5k	RTE 2.5k	Average -
Pre-OpenAI SOTA	80.6/80.1	66.1	82.3	93.2	35.0	81.0	86.0	61.7	74.0
BiLSTM+ELMo+Attn	76.4/76.1	64.8	79.8	90.4	36.0	73.3	84.9	56.8	71.0
OpenAI GPT	82.1/81.4	70.3	87.4	91.3	45.4	80.0	82.3	56.0	75.1
BERT <sub>BASE</sub>	84.6/83.4	71.2	90.5	93.5	52.1	85.8	88.9	66.4	79.6
BERT <sub>LARGE</sub>	<b>86.7/85.9</b>	<b>72.1</b>	<b>92.7</b>	<b>94.9</b>	<b>60.5</b>	<b>86.5</b>	<b>89.3</b>	<b>70.1</b>	<b>82.1</b>

# Major Application



The Keyword

Latest Stories

Product Updates

Company News

SEARCH

## Understanding searches better than ever before

Pandu Nayak

Google Fellow and Vice President, Search

Published Oct 25, 2019

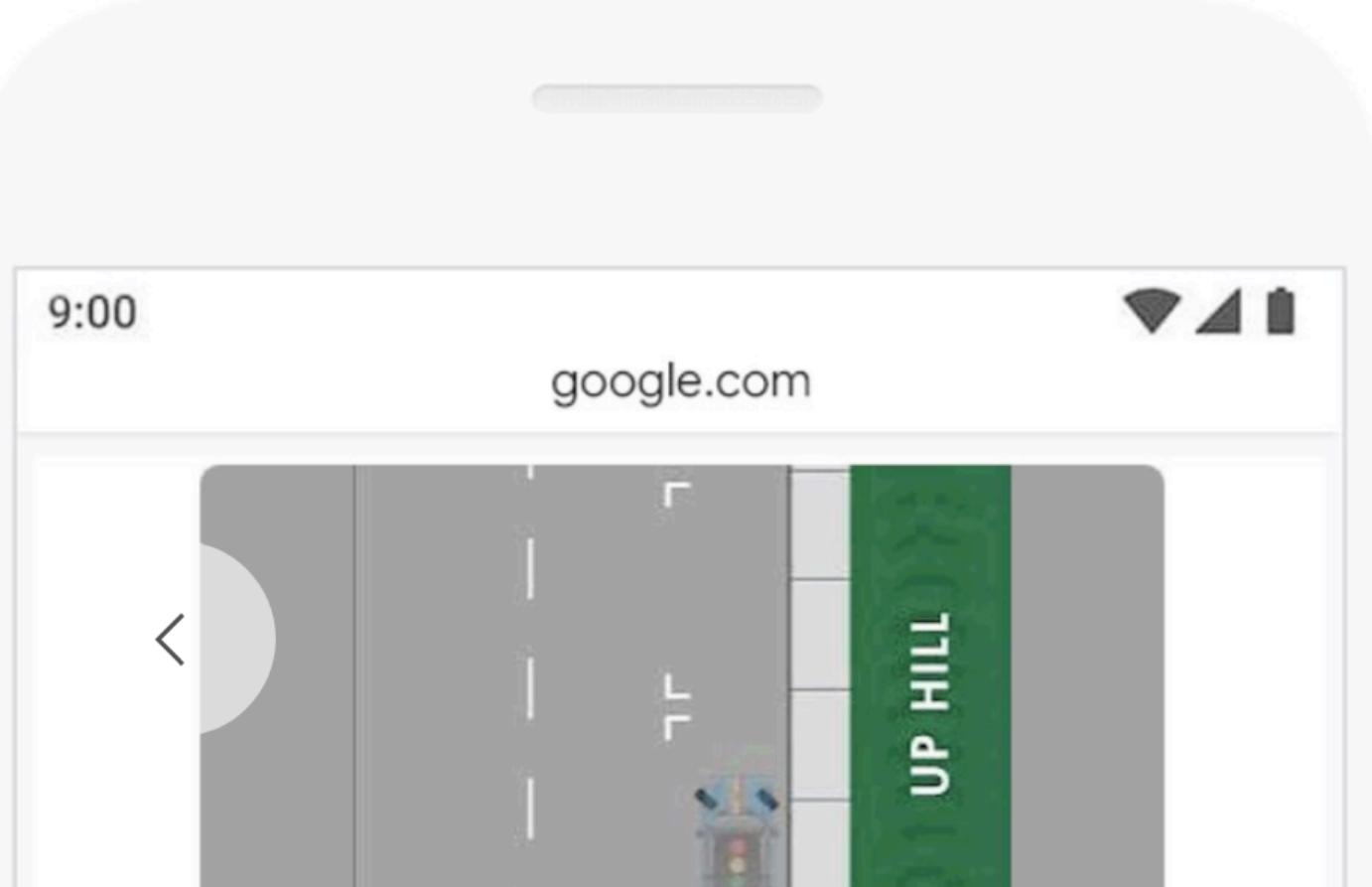
If there's one thing I've learned over the 15 years working on Google Search, it's that people's curiosity is endless. We see billions of searches every day, and 15 percent of those queries are ones we haven't seen before--so we've built ways to return results for queries we can't anticipate.

<https://www.blog.google/products/search/search-language-understanding-bert/>

# Major Application

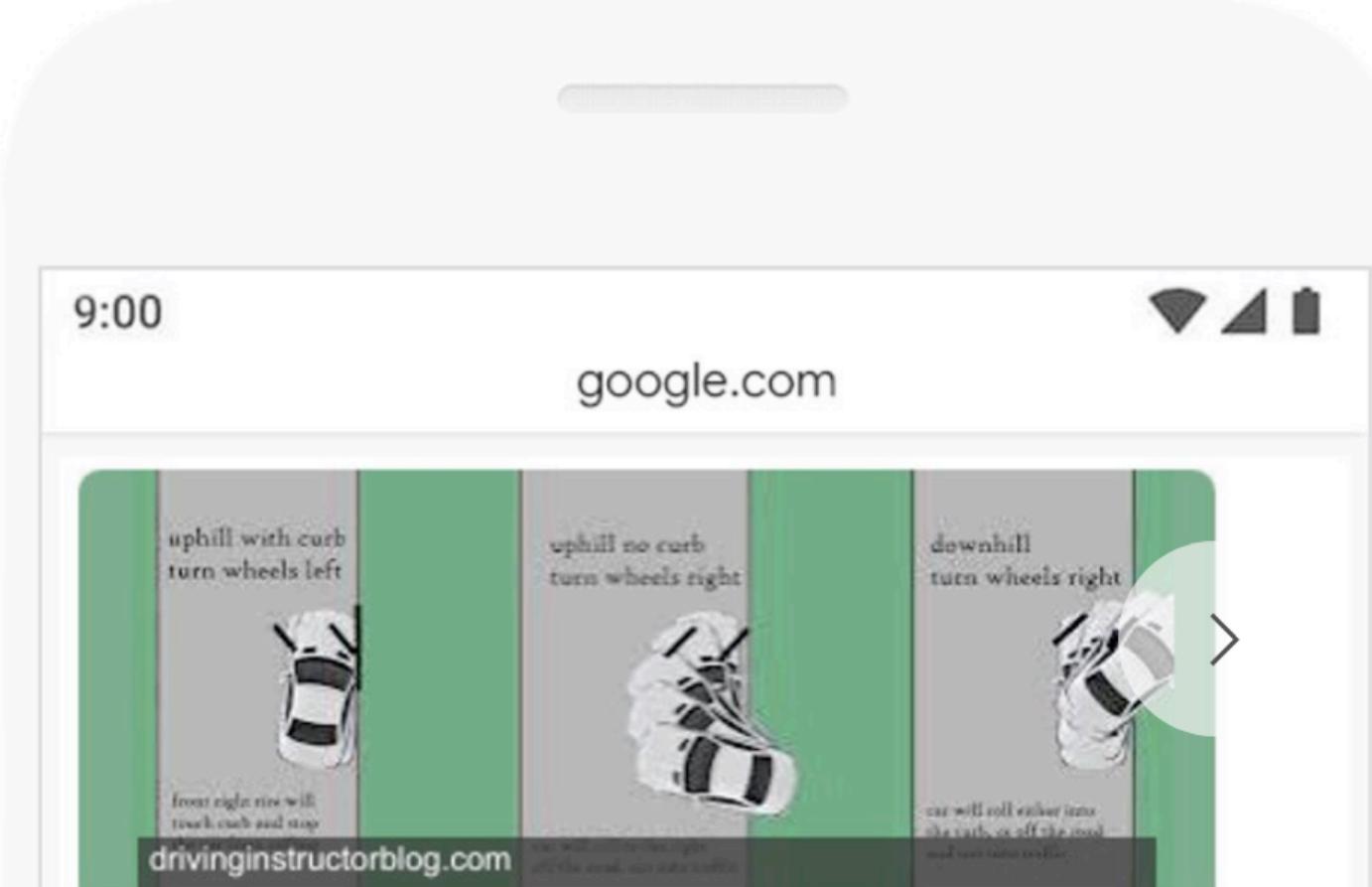
 parking on a hill with no curb

**BEFORE**



**Parking on a Hill.** Uphill: When headed uphill at a **curb**, turn the front wheels away from the **curb** and let your vehicle roll backwards slowly until the rear part of the front wheel rests against the **curb** using it as a block. Downhill: When you stop your car headed downhill, turn your front wheels

**AFTER**



For either uphill or downhill **parking**, if there is no **curb**, turn the wheels toward the side of the road so the car will roll away from the center of the road if the brakes fail. When you park on a sloping driveway, turn the wheels so that the car will not roll into the

Does BERT implicitly perform deep  
processing?

# WHAT DO YOU LEARN FROM CONTEXT? PROBING FOR SENTENCE STRUCTURE IN CONTEXTUALIZED WORD REPRESENTATIONS

**Ian Tenney,<sup>\*1</sup> Patrick Xia,<sup>2</sup> Berlin Chen,<sup>3</sup> Alex Wang,<sup>4</sup> Adam Poliak,<sup>2</sup>  
R. Thomas McCoy,<sup>2</sup> Najoung Kim,<sup>2</sup> Benjamin Van Durme,<sup>2</sup> Samuel R. Bowman,<sup>4</sup>  
Dipanjan Das,<sup>1</sup> and Ellie Pavlick<sup>1,5</sup>**

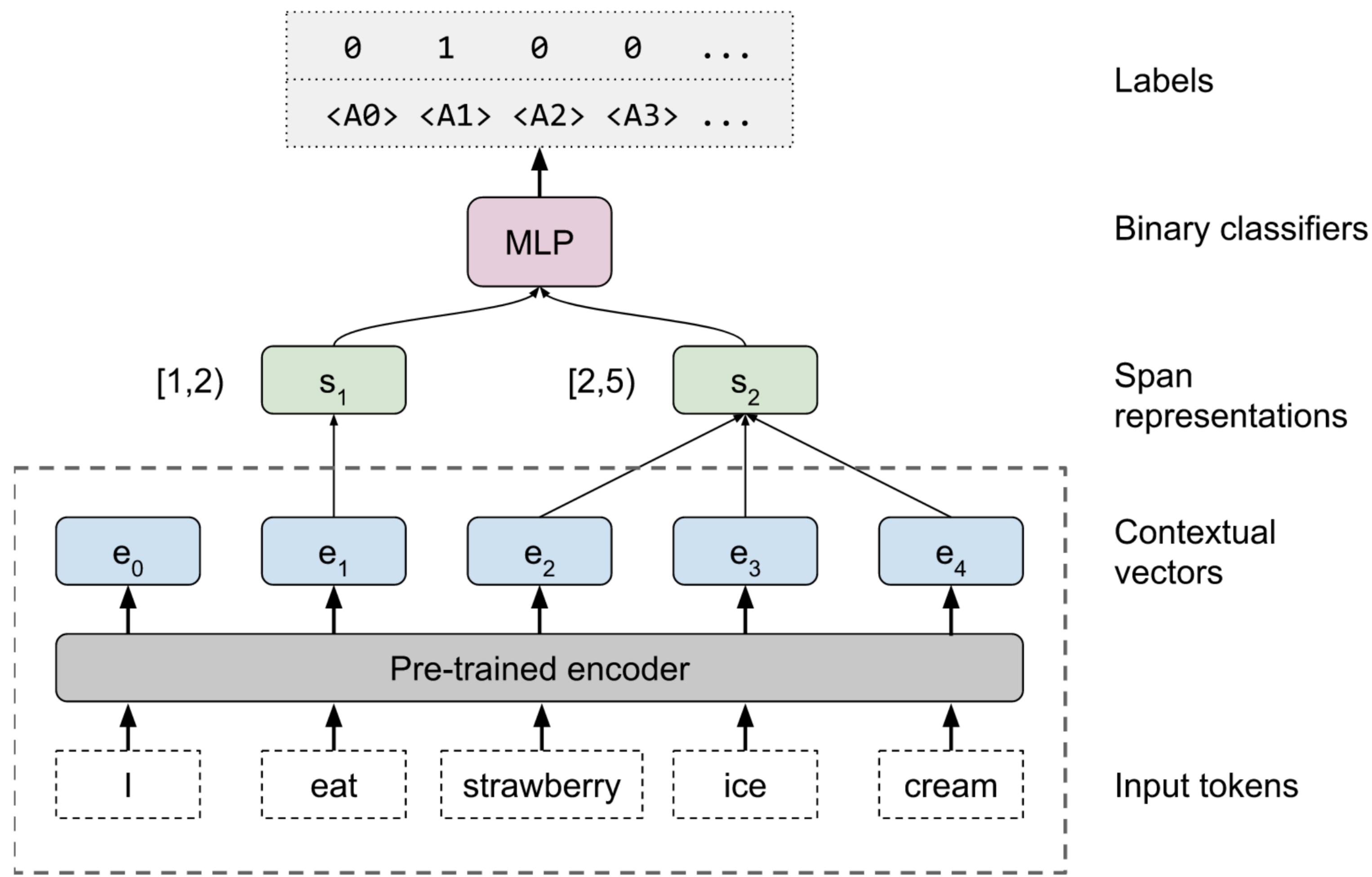
<sup>1</sup>Google AI Language, <sup>2</sup>Johns Hopkins University, <sup>3</sup>Swarthmore College,  
<sup>4</sup>New York University, <sup>5</sup>Brown University

[Tenney et al 2019](#)

## ABSTRACT

Contextualized representation models such as ELMo (Peters et al., 2018a) and BERT (Devlin et al., 2018) have recently achieved state-of-the-art results on a diverse array of downstream NLP tasks. Building on recent token-level probing work, we introduce a novel *edge probing* task design and construct a broad suite of sub-sentence tasks derived from the traditional structured NLP pipeline. We probe word-level contextual representations from four recent models and investigate how they encode sentence structure across a range of syntactic, semantic, local, and long-range phenomena. We find that existing models trained on language modeling and translation produce strong representations for syntactic phenomena, but only offer comparably small improvements on semantic tasks over a non-contextual baseline.

# Edge Probing Set-up



# Results

	CoVe			ELMo			GPT		
	Lex.	Full	Abs. Δ	Lex.	Full	Abs. Δ	Lex.	cat	mix
Part-of-Speech	85.7	94.0	8.4	90.4	<b>96.7</b>	6.3	88.2	94.9	95.0
Constituents	56.1	81.6	25.4	69.1	<b>84.6</b>	15.4	65.1	81.3	<b>84.6</b>
Dependencies	75.0	83.6	8.6	80.4	<b>93.9</b>	13.6	77.7	92.1	<b>94.1</b>
Entities	88.4	90.3	1.9	92.0	<b>95.6</b>	3.5	88.6	92.9	92.5
SRL (all)	59.7	80.4	20.7	74.1	<b>90.1</b>	16.0	67.7	86.0	89.7
Core roles	56.2	<b>81.0</b>	24.7	73.6	<b>92.6</b>	19.0	65.1	88.0	92.0
Non-core roles	67.7	78.8	<i>11.1</i>	75.4	<b>84.1</b>	8.8	73.9	81.3	<b>84.1</b>
OntoNotes coref.	72.9	79.2	6.3	75.3	84.0	8.7	71.8	83.6	<b>86.3</b>
SPR1	73.7	77.1	3.4	80.1	<b>84.8</b>	4.7	79.2	83.5	83.1
SPR2	76.6	80.2	3.6	82.1	83.1	1.0	82.2	<b>83.8</b>	<b>83.5</b>
Winograd coref.	52.1	<b>54.3</b>	2.2	<b>54.3</b>	<b>53.5</b>	-0.8	51.7	52.6	<b>53.8</b>
Rel. (SemEval)	51.0	60.6	9.6	55.7	77.8	22.1	58.2	<b>81.3</b>	<b>81.0</b>
Macro Average	69.1	78.1	9.0	75.4	<b>84.4</b>	9.1	73.0	83.2	<b>84.4</b>

	BERT-base						BERT-large					
	F1 Score			Abs. Δ			F1 Score			Abs. Δ		
	Lex.	cat	mix	ELMo	Lex.	cat	mix	(base)	ELMo			
Part-of-Speech	88.4	<b>97.0</b>	96.7	0.0	88.1	96.5	<b>96.9</b>	0.2	0.2			
Constituents	68.4	83.7	86.7	2.1	69.0	80.1	<b>87.0</b>	0.4	2.5			
Dependencies	80.1	93.0	95.1	1.1	80.2	91.5	<b>95.4</b>	0.3	1.4			
Entities	90.9	96.1	96.2	0.6	91.8	96.2	<b>96.5</b>	0.3	0.9			
SRL (all)	75.4	89.4	91.3	1.2	76.5	88.2	<b>92.3</b>	1.0	2.2			
Core roles	74.9	<b>91.4</b>	<b>93.6</b>	<i>1.0</i>	76.3	89.9	<b>94.6</b>	<i>1.0</i>	2.0			
Non-core roles	76.4	84.7	85.9	<i>1.8</i>	76.9	84.1	<b>86.9</b>	<i>1.0</i>	2.8			
OntoNotes coref.	74.9	88.7	90.2	6.3	75.7	89.6	<b>91.4</b>	1.2	7.4			
SPR1	79.2	84.7	<b>86.1</b>	1.3	79.6	85.1	<b>85.8</b>	-0.3	1.0			
SPR2	81.7	83.0	<b>83.8</b>	0.7	81.6	83.2	<b>84.1</b>	0.3	1.0			
Winograd coref.	54.3	53.6	54.9	1.4	53.0	53.8	<b>61.4</b>	6.5	7.8			
Rel. (SemEval)	57.4	78.3	82.0	4.2	56.2	77.6	<b>82.4</b>	0.5	4.6			
Macro Average	75.1	84.8	86.3	1.9	75.2	84.2	<b>87.3</b>	1.0	2.9			

# Conclusion

- “in general, contextualized embeddings improve over their non-contextualized counterparts largely on syntactic tasks(e.g. constituent labeling) in comparison to semantic tasks (e.g. coreference), suggesting that these embeddings encode syntax more so than higher-level semantics”

# BERT RedisCOVERS THE CLASSICAL NLP PIPELINE

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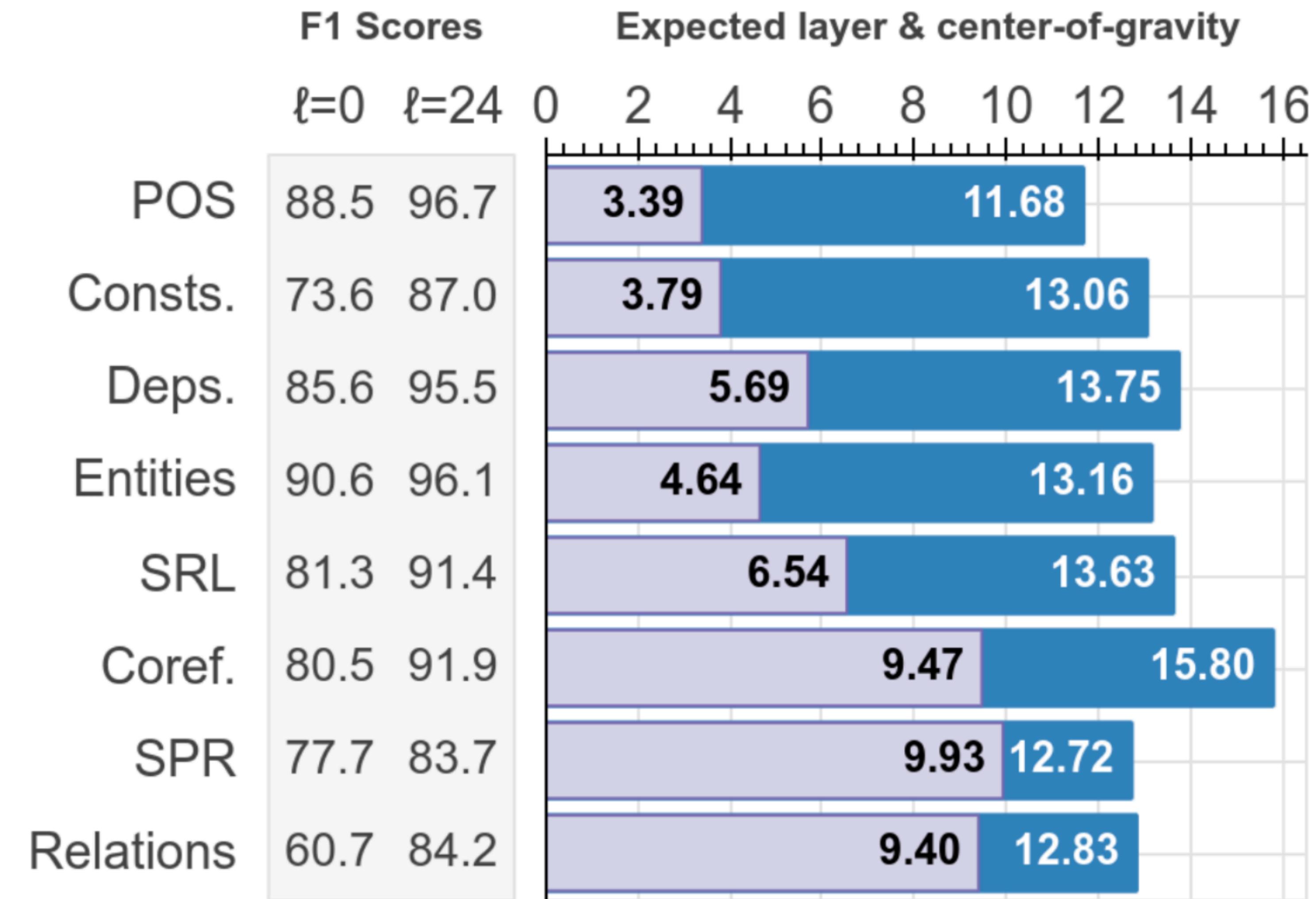
## Abstract

Pre-trained text encoders have rapidly advanced the state of the art on many NLP tasks. We focus on one such model, BERT, and aim to quantify where linguistic information is captured within the network. We find that the model represents the steps of the traditional NLP pipeline in an interpretable and localizable way, and that the regions responsible for each step appear in the expected sequence: POS tagging, parsing, NER, semantic roles, then coreference. Qualitative analysis reveals that the model can and often does adjust this pipeline dynamically, revising lower-level decisions on the basis of disambiguating information from higher-level representations.

of the network directly, to assess whether there exist localizable regions associated with distinct types of linguistic decisions. Such work has produced evidence that deep language models can encode a range of syntactic and semantic information (e.g. Shi et al., 2016; Belinkov, 2018; Tenney et al., 2019), and that more complex structures are represented hierarchically in the higher layers of the model (Peters et al., 2018b; Blevins et al., 2018).

We build on this latter line of work, focusing on the BERT model (Devlin et al., 2019), and use a suite of probing tasks (Tenney et al., 2019) derived from the traditional NLP pipeline to quantify where specific types of linguistic information are

Tenney et al 2019



# A Structural Probe for Finding Syntax in Word Representations

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**Christopher D. Manning**

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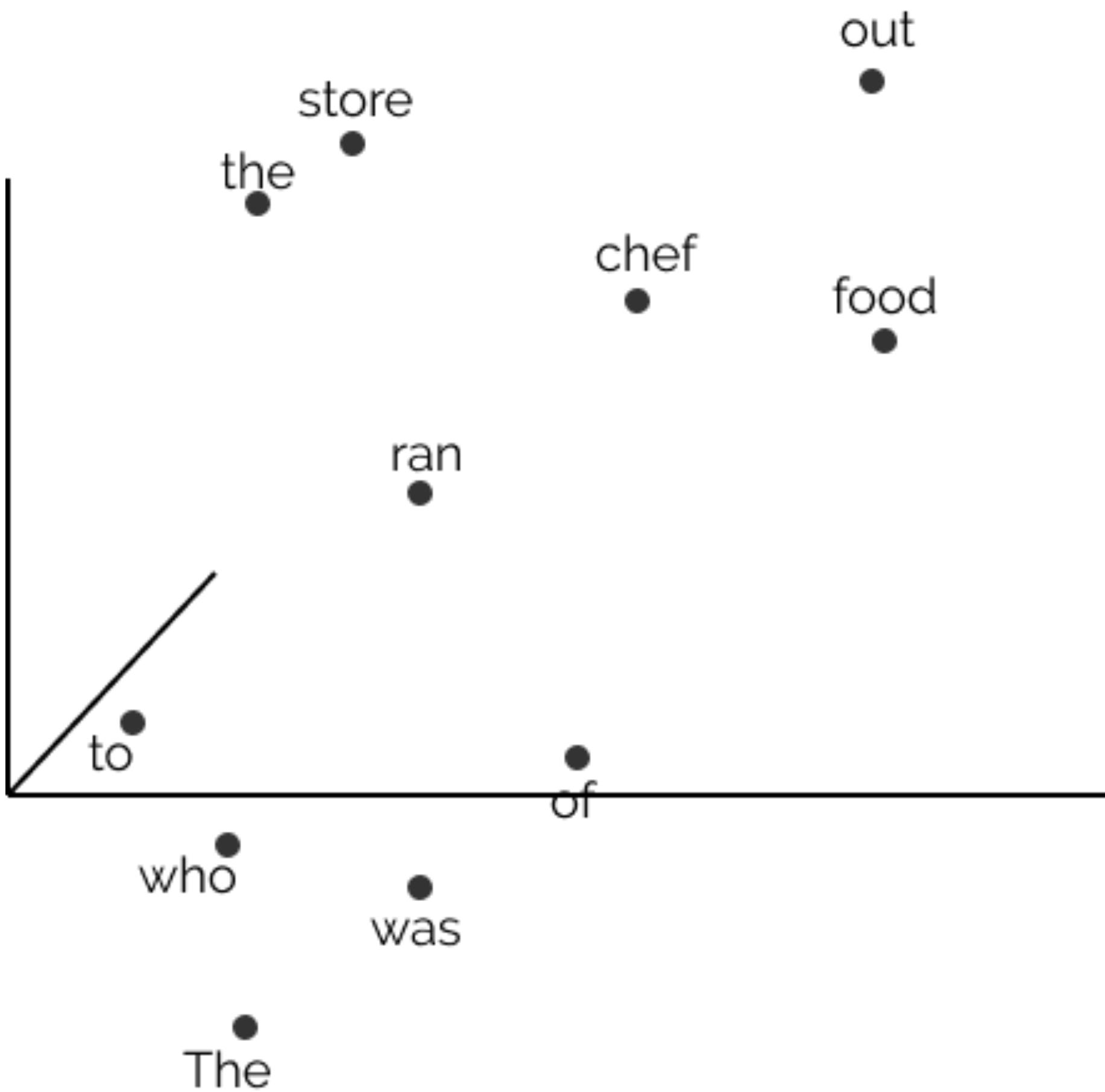
## Abstract

Recent work has improved our ability to detect linguistic knowledge in word representations. However, current methods for detecting syntactic knowledge do not test whether syntax trees are represented in their entirety. In this work, we propose a *structural probe*, which evaluates whether syntax trees are embedded in a linear transformation of a neural network’s word representation space. The probe identifies a linear transformation under which squared L2 distance encodes the distance between words in the parse tree, and one in which squared L2 norm encodes depth in the parse tree. Using our probe, we show

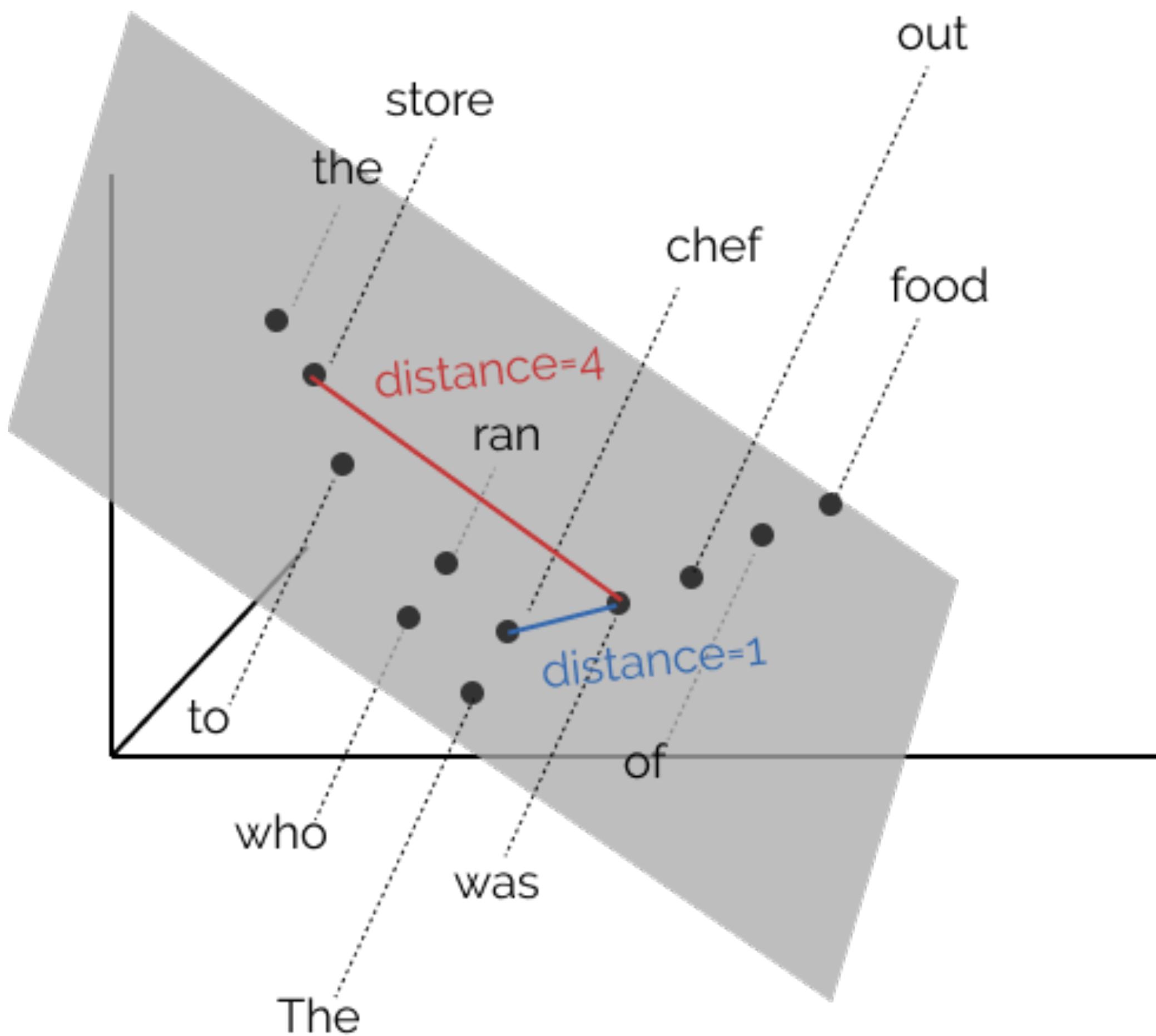
In this work, we propose a *structural probe*, a simple model which tests whether syntax trees are consistently embedded in a linear transformation of a neural network’s word representation space. Tree structure is embedded if the transformed space has the property that squared L2 distance between two words’ vectors corresponds to the number of edges between the words in the parse tree. To reconstruct edge directions, we hypothesize a linear transformation under which the squared L2 norm corresponds to the depth of the word in the parse tree. Our probe uses supervision to find the transformations under which these properties are best approximated for each model. If such transfor-

Hewitt and Manning 2019  
blog post

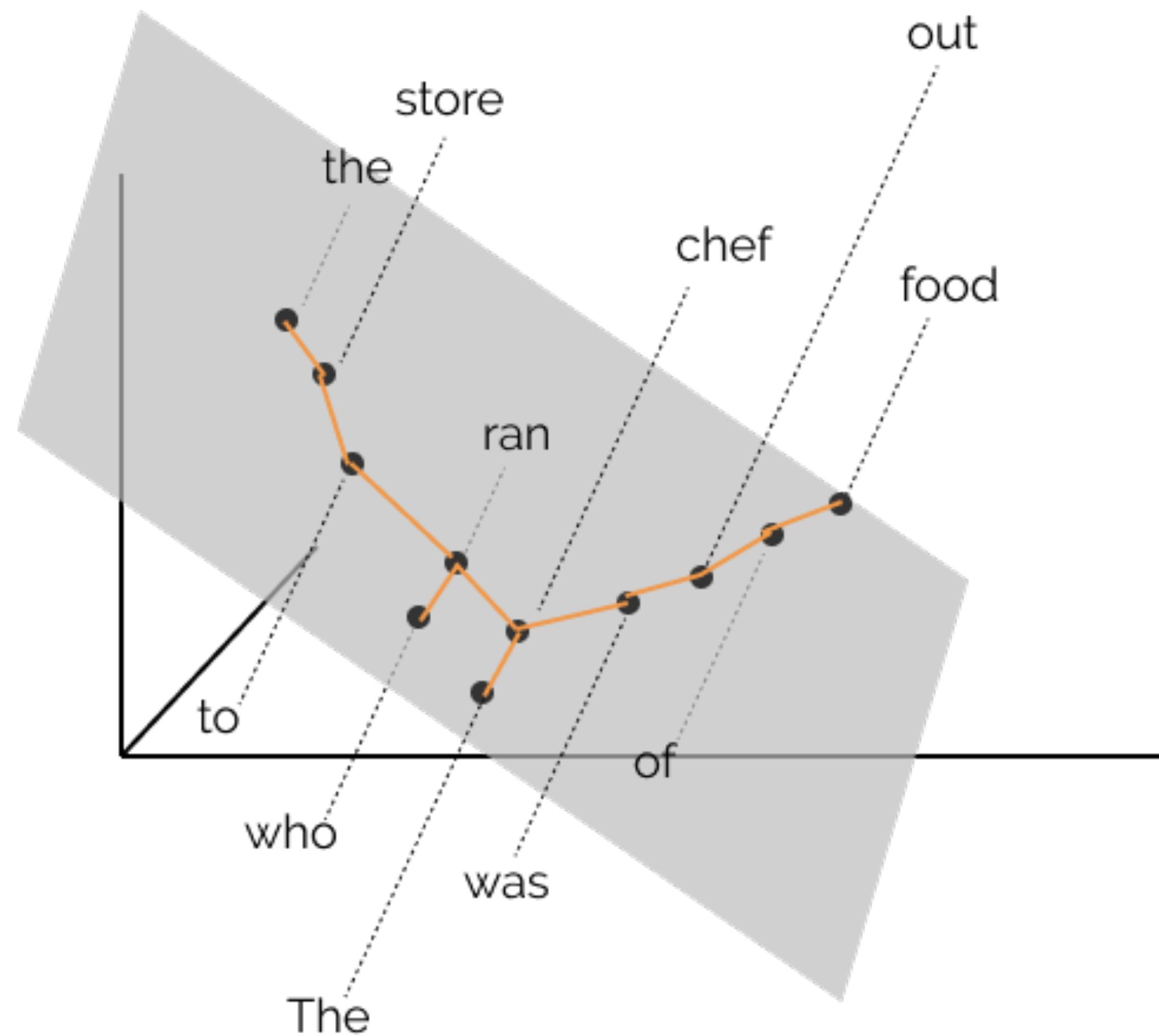
“The chef who ran to the store was out of food.”



# “The chef who ran to the store was out of food.”



# “The chef who ran to the store was out of food.”



# Results

Method	Distance		Depth	
	UUAS	DSpr.	Root%	NSpr.
LINEAR	48.9	0.58	2.9	0.27
ELMo0	26.8	0.44	54.3	0.56
DECAY0	51.7	0.61	54.3	0.56
PROJ0	59.8	0.73	64.4	0.75
ELMo1	77.0	0.83	86.5	0.87
BERTBASE7	79.8	0.85	88.0	0.87
BERTLARGE15	<b>82.5</b>	0.86	89.4	0.88
BERTLARGE16	81.7	<b>0.87</b>	<b>90.1</b>	<b>0.89</b>

[SOTA: directed UAS >97%]

# Examples

**BERTlarge16**

The complex financing plan in the S+L bailout law includes raising \$ 30 billion from debt issued by the newly created RTC .

**ELMo1**

The complex financing plan in the S+L bailout law includes raising \$ 30 billion from debt issued by the newly created RTC .

**Proj0**

The complex financing plan in the S+L bailout law includes raising \$ 30 billion from debt issued by the newly created RTC .

Black = gold parse.

Model parses: Maximum Spanning Tree from distances in transformed space.

# **Right for the Wrong Reasons: Diagnosing Syntactic Heuristics in Natural Language Inference**

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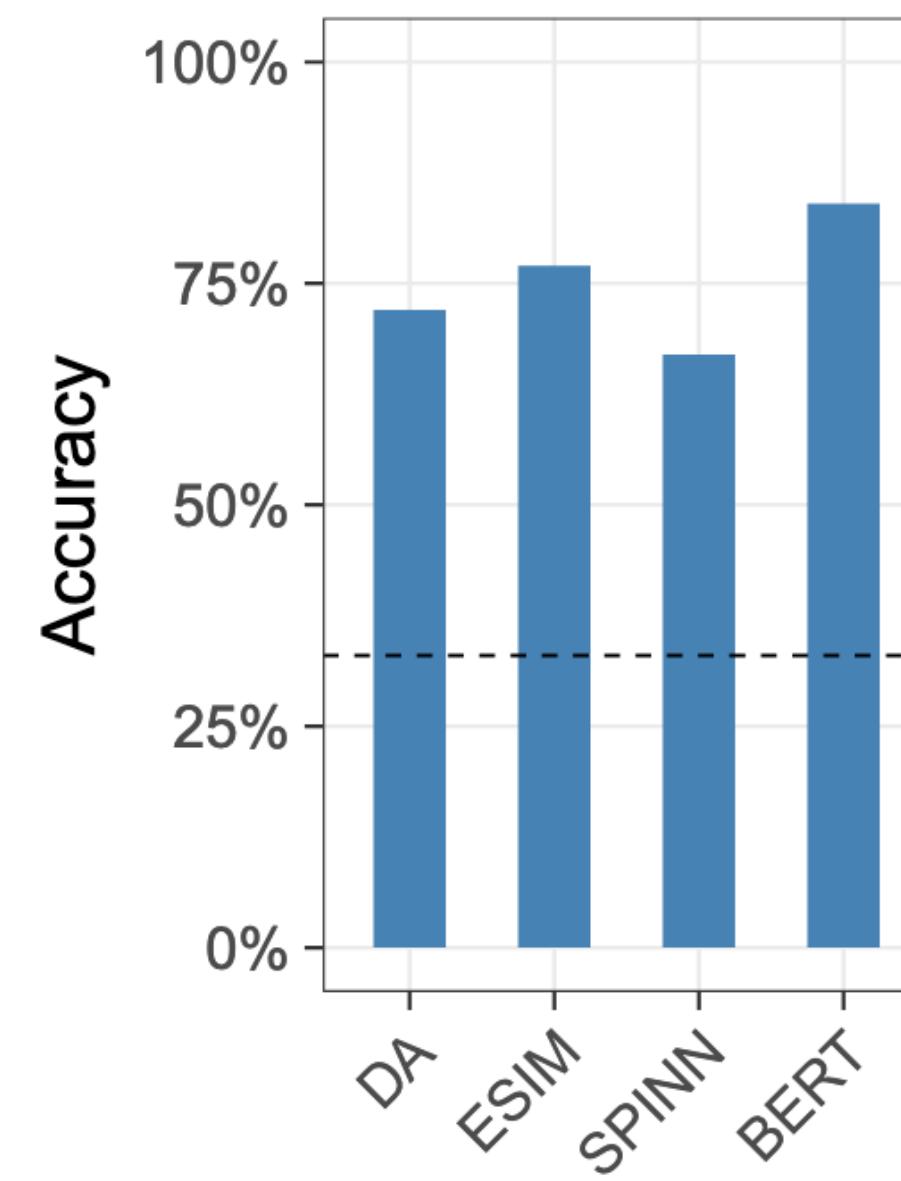
McCoy et al 2019

# Main Idea

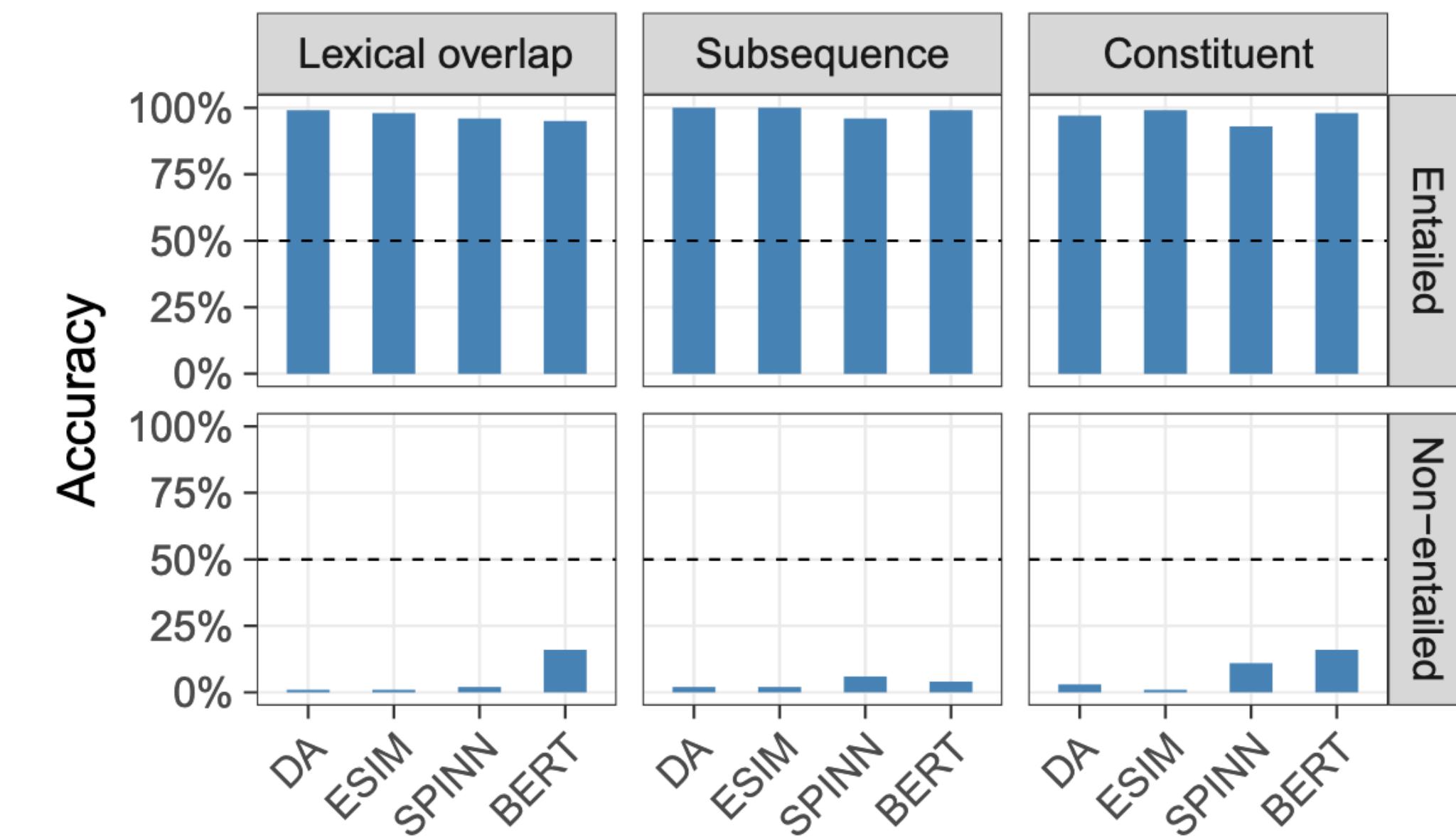
- BERT et al do really well on natural language understanding tasks like NLI (natural language inference)
- Do they do so “for the right reasons”?
- In other words:
  - Or does solving the existing datasets mean they’ve solved the task?
  - Or can success reflect other features than deep language understanding?

Heuristic	Premise	Hypothesis	Label
Lexical overlap heuristic	The banker near the judge saw the actor.	The banker saw the actor.	E
	The lawyer was advised by the actor.	The actor advised the lawyer.	E
	The doctors visited the lawyer.	The lawyer visited the doctors.	N
	The judge by the actor stopped the banker.	The banker stopped the actor.	N
Subsequence heuristic	The artist and the student called the judge.	The student called the judge.	E
	Angry tourists helped the lawyer.	Tourists helped the lawyer.	E
	The judges heard the actors resigned.	The judges heard the actors.	N
	The senator near the lawyer danced.	The lawyer danced.	N
Constituent heuristic	Before the actor slept, the senator ran.	The actor slept.	E
	The lawyer knew that the judges shouted.	The judges shouted.	E
	If the actor slept, the judge saw the artist.	The actor slept.	N
	The lawyers resigned, or the artist slept.	The artist slept.	N

# Results



(a)



(b)

(performance improves if fine-tuned on this challenge set)

# Summary

- Pre-trained encoders are very powerful
- Transfer learning from them often leads to very strong performance on NLP tasks
- Why?
  - Some evidence of *some* internal deep processing (esp. syntax)
  - Very clever exploitation of spurious correlations in the data

# Course Recap / Highlights

# Wrapping Up

# Deep Processing

- Building of deep linguistic structures for NLP
  - Syntax
  - Semantics
  - Pragmatics
- Used and useful in many applications, e.g.
  - IR/QA/search
  - Conversational AI

# Syntax

- Constituency Parsing
  - (P)CFGs
  - Grammar induction
- Dependency Parsing
  - Transition vs. MST based parsers

# CKY Parsing Example

## $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

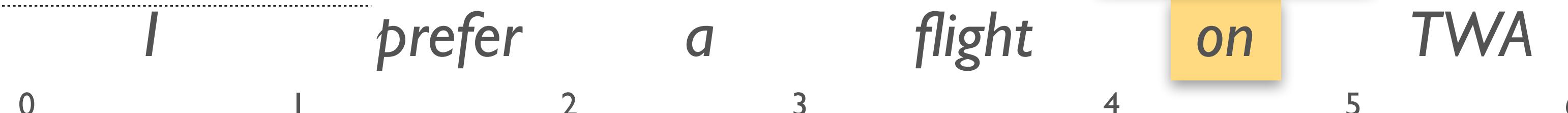
$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**Verb, VP, S**  
[1,2]

**Verb, VP, S**  
[1,3]

**VP, X2, S**  
[1,4]

**Det**  
[2,3]

**NP**  
[2,4]

**Noun, Nom**  
[3,4]

**Prep**  
[4,5]

## Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

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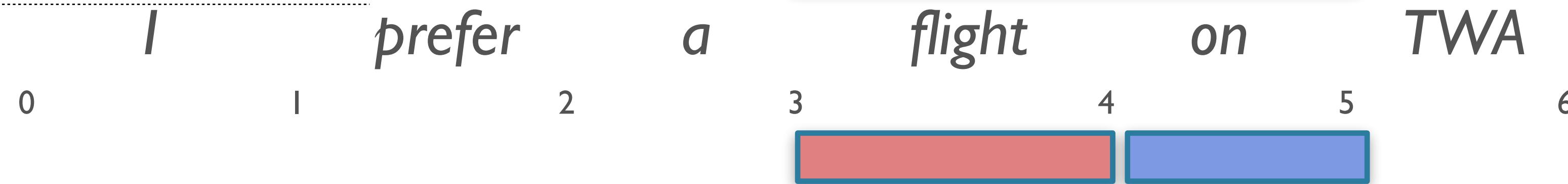
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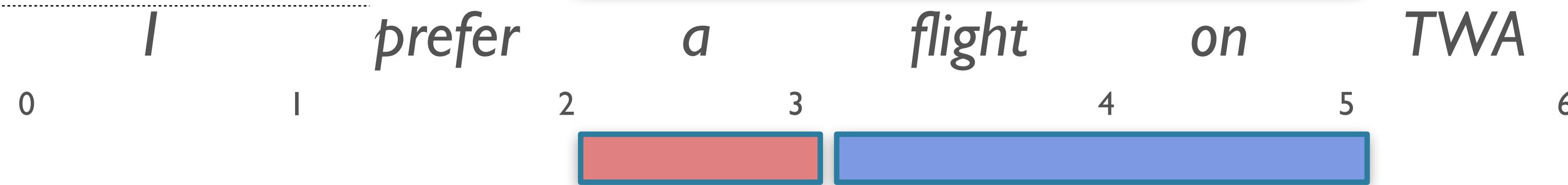
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<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]	<b>S</b> [0,3]	<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		
		<b>Det</b> [2,3]	<b>NP</b> [2,4]	<b>NP</b> [2,5]	
			<b>Noun, Nom</b> [3,4]	<b>Det</b> [3,5]	
				<b>Prep</b> [4,5]	

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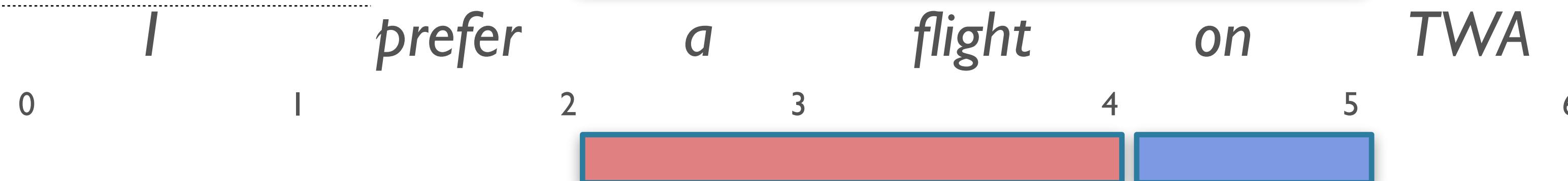
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NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]		
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$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

### NP, Pronoun

[0,1]

### S

[0,2]

### S

[0,3]

### S

[0,4]

### Verb, VP, S

[1,2]

### Verb, VP, S

[1,3]

### VP, X2, S

[1,4]

### VP, X2, S

[1,5]

### Det

[2,3]

### NP

[2,4]

### NP

[2,5]

### Noun, Nom

[3,4]

### Noun, Nom

[3,5]

### Prep

[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

---

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

---

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

---

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

---

$PP \rightarrow Preposition NP$

### NP, Pronoun

[0,1]

### S

[0,2]

### S

[0,3]

### S

[0,4]

### Verb, VP, S

[1,2]

### VP, X2, S

[1,3]

### NP

[1,4]

[1,5]

### Det

[2,3]

### NP

[2,4]

[2,5]

### Noun, Nom

[3,4]

### Prep

[3,5]

[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

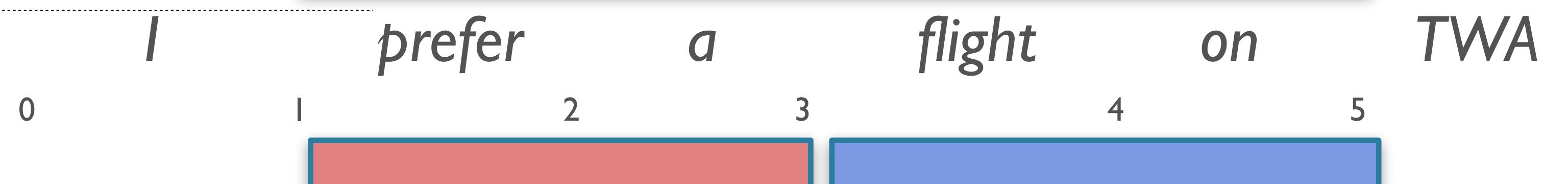
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

### NP, Pronoun

[0,1]

### S

[0,2]

### S

[0,3]

### S

[0,4]

### Verb, VP, S

[1,2]

### Det

[1,3]

### VP, X2, S

[1,4]

### NP

[1,5]

### Det

[2,3]

### Noun, Nom

[2,4]

### Prep

[2,5]

### Noun, Nom

[3,4]

### Prep

[3,5]

### Prep

[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

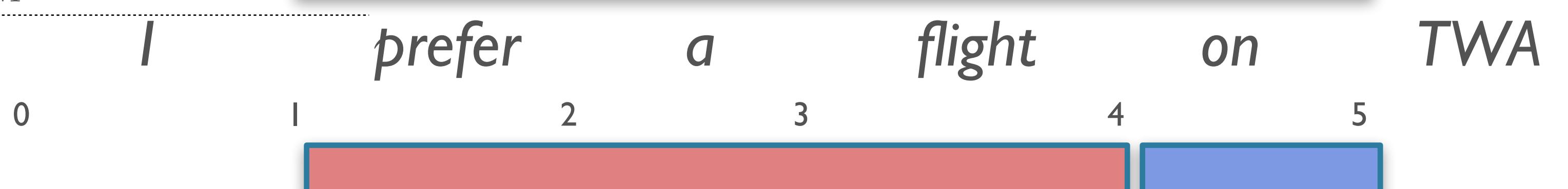
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**S**  
[0,5]

**Verb, VP, S**  
[1,2]

**Verb, VP, S**  
[1,3]

**Verb, VP, S**  
[1,4]

**VP, X2, S**  
[1,5]

**Det**  
[2,3]

**NP**  
[2,4]

**NP**  
[2,5]

**Noun, Nom**  
[3,4]

**Noun, Nom**  
[3,5]

**Prep**  
[4,5]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

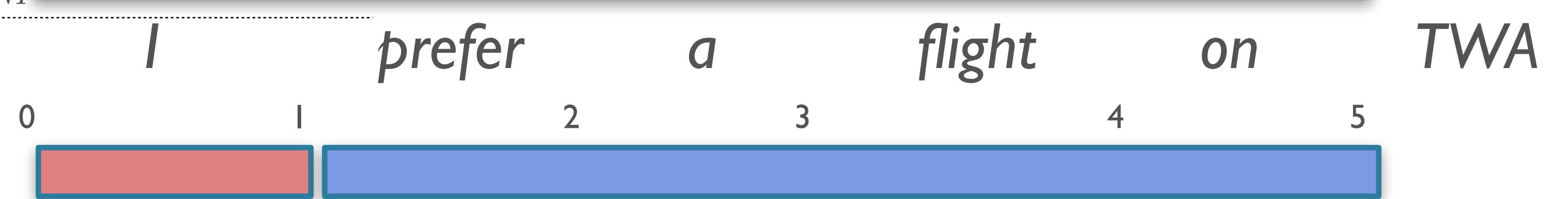
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

---

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

---

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

---

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

---

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

[0,2]

[0,3]

[0,4]

[0,5]

[1,2]

[1,3]

[1,4]

[1,5]

[2,3]

[2,4]

[2,5]

[3,4]

[3,5]

[4,5]

[4,6]

[4,7]

[4,8]

[4,9]

[4,10]

[4,11]

[4,12]

[4,13]

[4,14]

[4,15]

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[4,19]

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[4,31]

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[4,106]

[4,107]

[4,108]

[4,109]

[4,110]

[4,111]

[4,112]

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[4,116]

[4,117]

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[4,150]

[4,151]

[4,152]

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[4,154]

[4,155]

[4,156]

[4,157]

[4,158]

[4,159]

[4,160]</p

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]  
[1,2]

**S**  
[0,3]  
[1,3]  
[2,3]

**S**  
[0,4]  
[1,4]  
[2,4]  
[3,4]

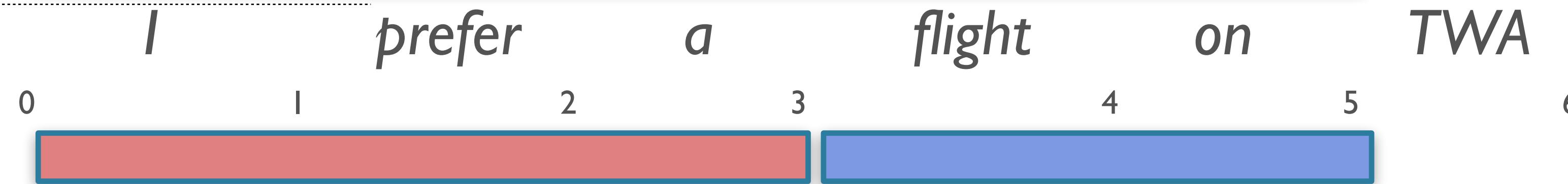
**Verb, VP, S**  
[0,5]  
[1,5]  
[2,5]  
[3,5]

**Det**  
**NP**  
[4,5]

**Noun, Nom**  
**Prep**  
[4,5]

**Lexicon**  
**Proper-Noun**  
**Aux**  
**Preposition**  
**Verb**

$Det \rightarrow that | this | a$   
 $Noun \rightarrow book | flight | meal | money$   
 $Pronoun \rightarrow I | she | me$   
 $Proper-Noun \rightarrow Houston | TWA$   
 $Aux \rightarrow does$   
 $Preposition \rightarrow from | to | on | near | through$   
 $Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**S**  
[0,5]

**Verb, VP, S**

[1,2]

**Verb, VP, S**

[1,3]

**Verb, VP, S**

[1,4]

**Verb, VP, S**

[1,5]

**VP, X2, S**

[1,6]

**VP, X2, S**

[1,7]

**VP, X2, S**

[1,8]

**VP, X2, S**

[1,9]

**VP, X2, S**

[1,10]

**VP, X2, S**

[1,11]

**VP, X2, S**

[1,12]

**VP, X2, S**

[1,13]

**VP, X2, S**

[1,14]

**VP, X2, S**

[1,15]

**VP, X2, S**

[1,16]

**VP, X2, S**

[1,17]

**VP, X2, S**

[1,18]

**VP, X2, S**

**NP**

[2,1]

**NP**

[2,2]

**NP**

[2,3]

**NP**

[2,4]

**NP**

[2,5]

**NP**

[2,6]

**NP**

[2,7]

**NP**

[2,8]

**NP**

[2,9]

**NP**

[2,10]

**NP**

[2,11]

**NP**

[2,12]

**NP**

[2,13]

**NP**

**Noun, Nom**

[3,1]

**Noun, Nom**

[3,2]

**Noun, Nom**

[3,3]

**Noun, Nom**

[3,4]

**Noun, Nom**

[3,5]

**Prep**

[4,1]

**Prep**

[4,2]

**Prep**

[4,3]

**Prep**

[4,4]

**Prep**

[4,5]

**Prep**

[4,6]

**Prep**

[4,7]

**Prep**

[4,8]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

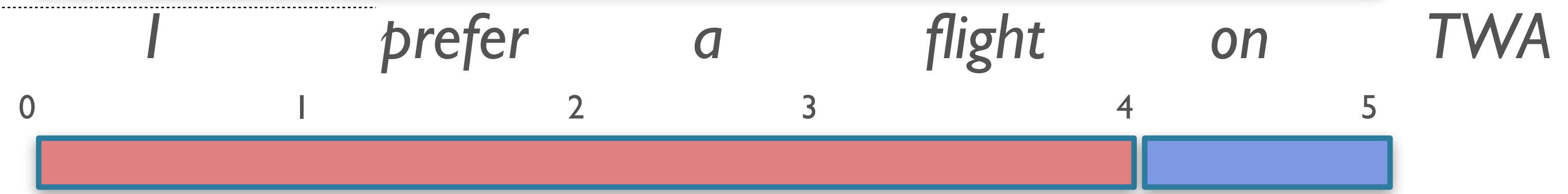
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



**NP,  
Pronoun**  
[0,1]

[0,2]

[1,2]

[2,3]

[3,4]

[4,5]

[5,6]

**S**

[0,3]

[1,3]

[2,4]

[3,5]

[4,5]

[5,6]

**Verb, VP, S**

[1,4]

[2,5]

[3,4]

[4,5]

[5,6]

**S**

[0,4]

[1,5]

[2,5]

[3,5]

[4,5]

[5,6]

**VP, X2, S**

[1,5]

[2,5]

[3,5]

[4,5]

[5,6]

**NP**

[2,4]

[3,5]

[4,5]

[5,6]

**Det**

[2,3]

[3,4]

[4,5]

[5,6]

**Prep**

[3,5]

[4,5]

[5,6]

**Verb**

[1,2]

[2,3]

[3,4]

[4,5]

[5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

**NNP, NP**

[5,6]

[5,6]

[5,6]

[5,6]

[5,6]

**NP**

[5,6]

[5,6]

[5,6]

[5,6]

[5,6]

[5,6]

[5,6]

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

**NP,  
Pronoun**  
[0,1]

**S**  
[0,2]

**S**  
[0,3]

**S**  
[0,4]

**S**  
[0,5]

**Verb, VP, S**

[1,2]

**Verb, VP, S**

[1,3]

**Det**

[2,3]

**Det**

[2,4]

**NP**

[2,5]

**Noun, Nom**

[3,4]

**Noun, Nom**

[3,5]

**Prep**

[4,5]

**PP**

[4,6]

**NNP, NP**

[5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

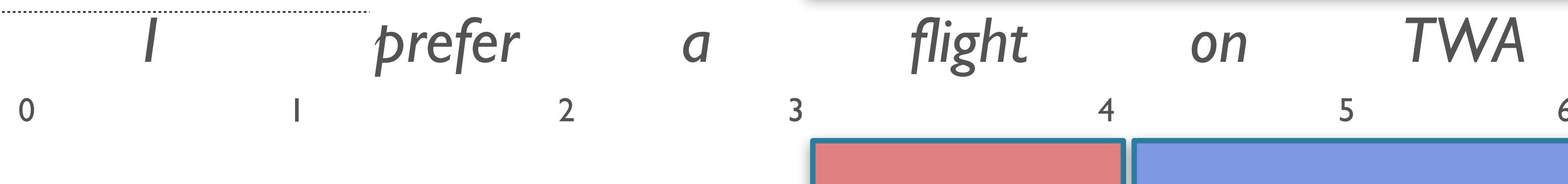
$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



**NP,  
Pronoun**  
[0,1]

[0,2]  
[1,2]

[0,3]  
[1,3]

[0,4]  
[1,4]

[0,5]  
[1,5]

[2,3]  
[2,4]

[2,4]  
[2,5]

[3,4]  
[3,5]

[3,5]  
[3,6]

**S**  
[0,2]

**Verb, VP, S**  
[1,2]

**Det**  
[1,3]

**NP**  
[1,4]

**Noun, Nom**  
[1,5]

**Prep**  
[2,3]

**PP**  
[2,4]

**NNP, NP**  
[2,5]

**Nom**  
[2,6]

**S**  
[0,4]

**VP, X2, S**  
[1,4]

**Det**  
[1,5]

**NP**  
[1,6]

**Noun, Nom**  
[2,6]

**Prep**  
[3,5]

**PP**  
[3,6]

**NNP, NP**  
[4,6]

**Nom**  
[5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

---

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

---

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

---

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

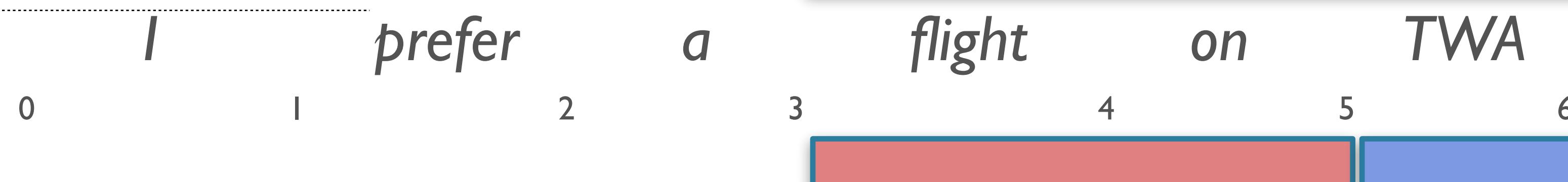
$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

---

$PP \rightarrow Preposition NP$



<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	[1,5]	
	<b>Det</b> [2,3]		<b>NP</b> [2,4]	[2,5]	
			<b>Noun, Nom</b> [3,4]	[3,5]	<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]
					<b>NNP, NP</b> [5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$

### $\mathcal{L}_1$ Grammar

$S \rightarrow NP VP$

$S \rightarrow X1 VP$

$X1 \rightarrow Aux NP$

$S \rightarrow book / include / prefer$

$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

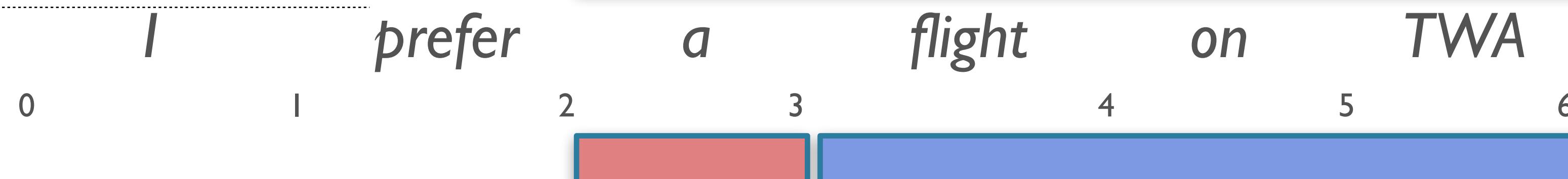
$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		
		<b>Det</b> [2,3]	<b>NP</b> [2,4]		<b>NP</b> [2,6]
				<b>Noun, Nom</b> [3,4]	<b>Nom</b> [3,6]
					<b>PP</b> [4,6]
				<b>Prep</b> [4,5]	<b>NNP, NP</b> [5,6]

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$NP \rightarrow Det Nominal$

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$Nominal \rightarrow Nominal Noun$

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$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

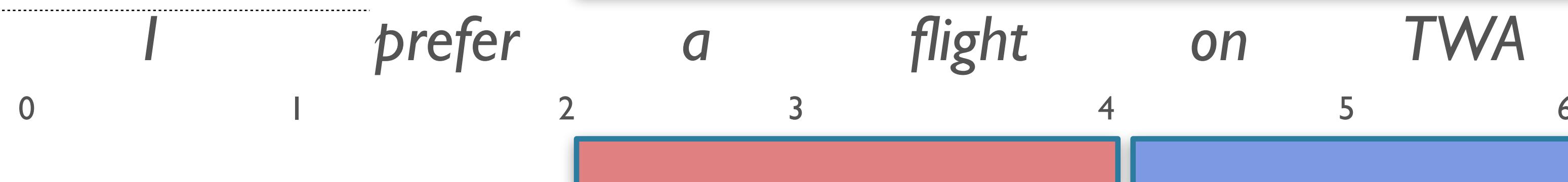
$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	[1,5]	
	<b>Det</b> [2,3]		<b>NP</b> [2,4]	[2,5]	<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]	[3,5]	<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]
					<b>NNP, NP</b> [5,6]

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$S \rightarrow Verb PP$

$S \rightarrow VP PP$

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$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

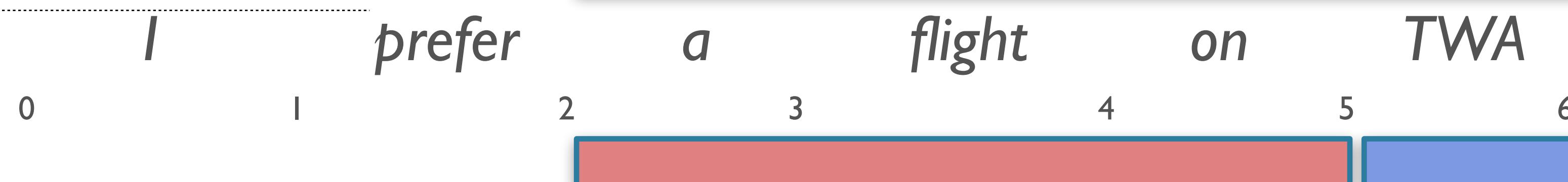
$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$



<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,4]		
	<b>Verb, VP, S</b> [1,2]	[1,3]	<b>VP, X2, S</b> [1,4]	[1,5]	
	<b>Det</b> [2,3]		<b>NP</b> [2,4]	[2,5]	<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]	[3,5]	<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]
					<b>NNP, NP</b> [5,6]

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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
		Verb, VP, S [1,2]		VP, X2, S [1,4]	
			Det [1,3]	NP [1,5]	NP [1,6]
					NP [2,6]
			Det [2,3]	NP [2,4]	Nom [3,6]
				Noun, Nom [3,4]	[3,5]
					PP [4,6]
				Prep [4,5]	NNP, NP [5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

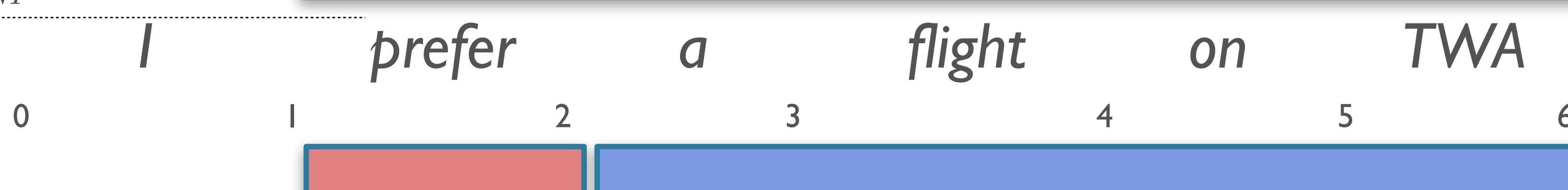
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	VP [1,6]
	<b>Verb, VP, S [1,2]</b>		<b>VP, X2, S [1,4]</b>		<b>VP [1,6]</b>
		<b>Det [1,3]</b>	<b>NP [2,4]</b>	<b>NP [1,5]</b>	<b>NP [2,6]</b>
			<b>Noun, Nom [3,4]</b>	<b>Nom [3,5]</b>	<b>Nom [3,6]</b>
				<b>Prep [4,5]</b>	<b>PP [4,6]</b>
					<b>NNP, NP [5,6]</b>

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

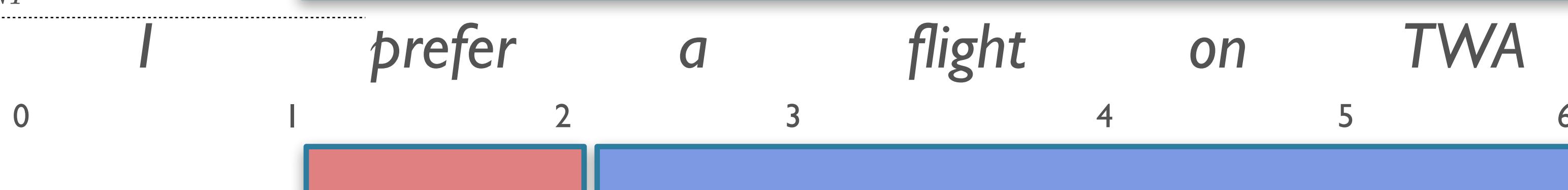
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

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$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,3]		<b>VP, X2</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [1,4]	<b>NP</b> [1,5]	<b>NP</b> [2,6]
			<b>Noun, Nom</b> [2,4]		<b>Nom</b> [3,6]
			<b>Noun, Nom</b> [3,4]	<b>Prep</b> [3,5]	<b>PP</b> [4,6]
					<b>NNP, NP</b> [5,6]

### Lexicon

$Det \rightarrow that | this | a$

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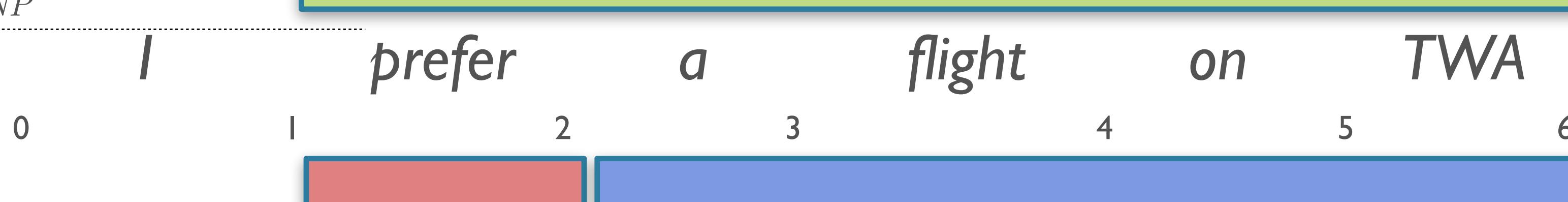
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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 $S \rightarrow X1 VP$   
 $X1 \rightarrow Aux NP$   
 $S \rightarrow book / include / prefer$   
 $S \rightarrow Verb NP$   
 $S \rightarrow X2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$

$NP \rightarrow I / she / me$

$NP \rightarrow TWA / Houston$

$NP \rightarrow Det Nominal$

$Nominal \rightarrow book / flight / meal / money$

$Nominal \rightarrow Nominal Noun$

$Nominal \rightarrow Nominal PP$

$VP \rightarrow book / include / prefer$

$VP \rightarrow Verb NP$

$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,3]		<b>VP, X2, S</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [2,4]		<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
				<b>Prep</b> [4,5]	<b>PP</b> [4,6]
					<b>NNP, NP</b> [5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

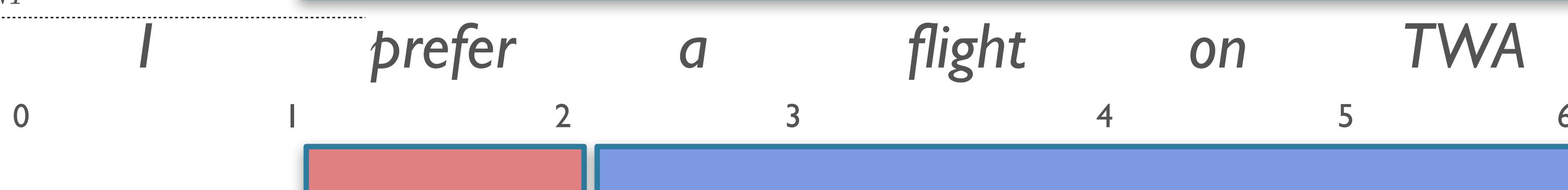
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



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$S \rightarrow Verb PP$

$S \rightarrow VP PP$

$NP \rightarrow I / she / me$

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$NP \rightarrow Det Nominal$

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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,3]		<b>VP, X2, S</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [1,4]	<b>NP</b> [1,5]	<b>NP</b> [2,6]
			<b>Noun, Nom</b> [2,4]		<b>Nom</b> [3,6]
			<b>Noun, Nom</b> [3,4]	<b>Prep</b> [3,5]	<b>PP</b> [4,6]
				<b>Prep</b> [4,5]	<b>NNP, NP</b> [5,6]

### Lexicon

$Det \rightarrow that | this | a$

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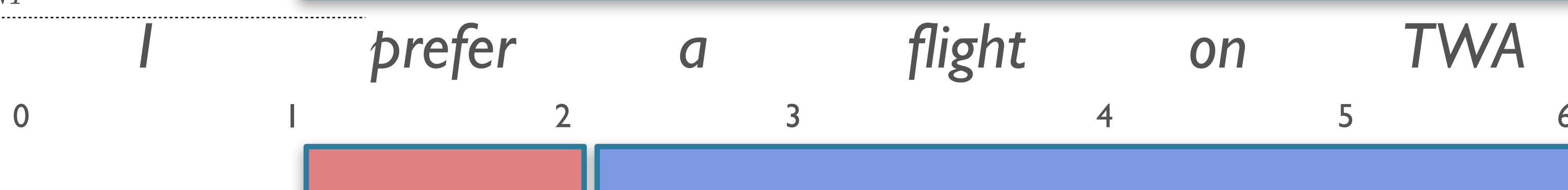
$Pronoun \rightarrow I | she | me$

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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
		<b>Verb, VP, S [1,2]</b>		<b>VP, X2, S [1,4]</b>	<b>VP, X2, S [1,6]</b>
			<b>Det [1,3]</b>	<b>NP [1,5]</b>	<b>NP [1,6]</b>
			<b>Det [2,3]</b>	<b>NP [2,4]</b>	<b>NP [2,6]</b>
				<b>Noun, Nom [3,4]</b>	<b>Nom [3,6]</b>
				<b>Prep [3,5]</b>	<b>PP [3,6]</b>
					<b>NNP, NP [4,6]</b>
					<b>NNP, NP [5,6]</b>

### Lexicon

$Det \rightarrow that | this | a$

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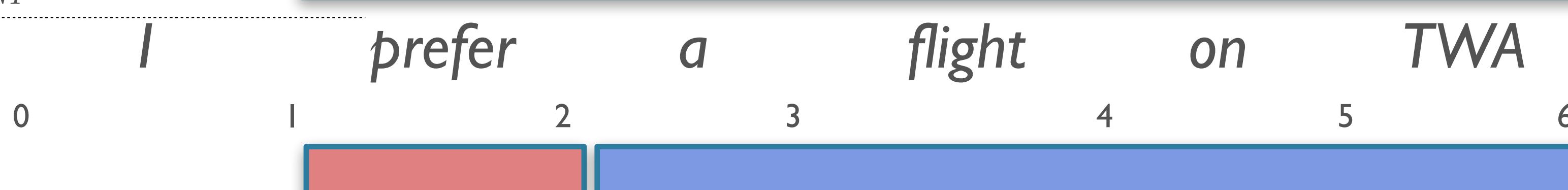
$Pronoun \rightarrow I | she | me$

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$Aux \rightarrow does$

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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

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NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
		Verb, VP, S [1,2]	VP, X2, S [1,3]		VP, X2, S [1,6]
			Det [2,3]	NP [2,4]	NP [2,6]
				Noun, Nom [3,4]	Nom [3,6]
					PP [4,5]
					NNP, NP [5,6]

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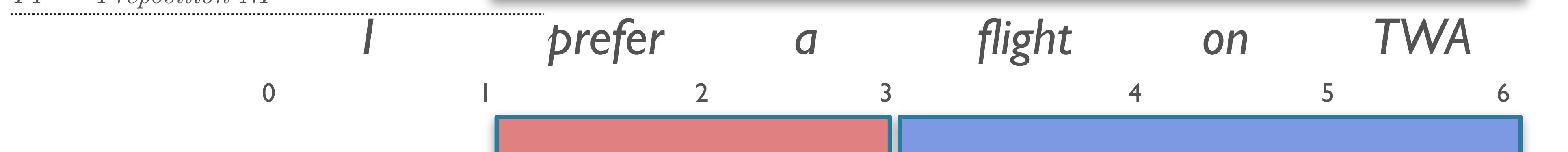
$Pronoun \rightarrow I | she | me$

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$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

<b>NP, Pronoun</b> [0,1]	<b>S</b> [0,2]		<b>S</b> [0,3]		<b>S</b> [0,4]		<b>S</b> [0,5]	
		<b>Verb, VP, S</b> [1,2]			<b>VP, X2, S</b> [1,4]			<b>VP, X2, S</b> [1,6]
				<b>Det</b> [1,3]		<b>NP</b> [2,4]		<b>NP</b> [2,6]
						<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
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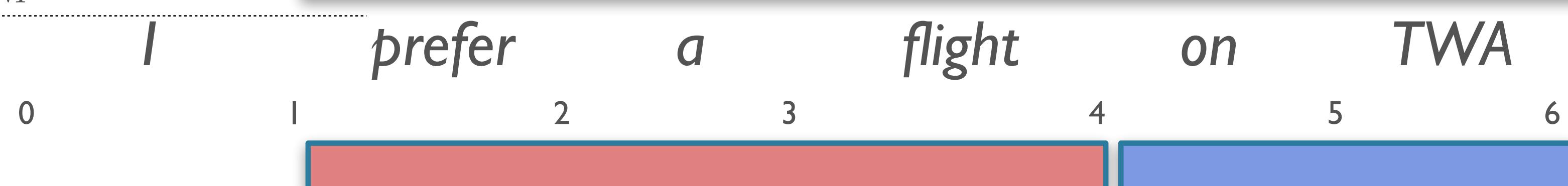
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$VP \rightarrow X2 PP$

$X2 \rightarrow Verb NP$

$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]		S [0,3]		S [0,4]		[0,5]	
		Verb, VP, S [1,2]			VP, X2, S [1,4]			VP, X2, S [1,6]
				Det [1,3]		NP [1,5]		
								NP [2,6]
								Nom [3,6]
								PP [4,6]
								NNP, NP [5,6]

### Lexicon

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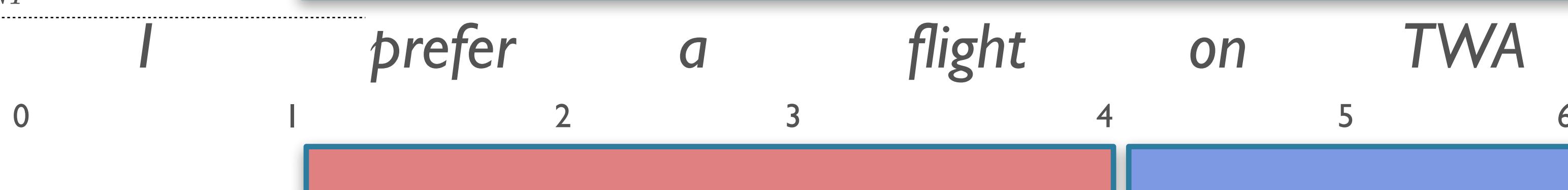
$Pronoun \rightarrow I | she | me$

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$VP \rightarrow Verb PP$

$VP \rightarrow VP PP$

$PP \rightarrow Preposition NP$

NP, Pronoun [0,1]	S [0,2]		S [0,3]	S [0,4]	[0,5]	
		Verb, VP, S [1,2]		VP, X2, S [1,4]		VP, X2, S [1,6]
			Det [1,3]	NP [2,4]	[1,5]	NP [2,6]
				Noun, Nom [3,4]	[3,5]	Nom [3,6]
					Prep [4,5]	PP [4,6]
						NNP, NP [5,6]

### Lexicon

$Det \rightarrow that | this | a$

$Noun \rightarrow book | flight | meal | money$

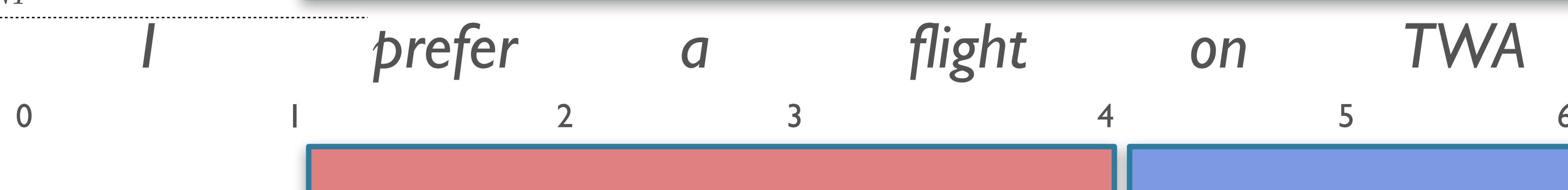
$Pronoun \rightarrow I | she | me$

$Proper-Noun \rightarrow Houston | TWA$

$Aux \rightarrow does$

$Preposition \rightarrow from | to | on | near | through$

$Verb \rightarrow book | include | prefer$



### $\mathcal{L}_1$ Grammar

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$S \rightarrow Verb NP$

$S \rightarrow X2 PP$

$S \rightarrow Verb PP$

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NP, Pronoun [0,1]	S [0,2]		S [0,3]	S [0,4]	[0,5]	
		Verb, VP, S [1,2]		VP, X2, S [1,4]		VP, X2, S [1,6]
			Det [1,3]	NP [2,4]		NP [2,6]
					Det [2,5]	
				Noun, Nom [3,4]		Nom [3,6]
					Prep [3,5]	
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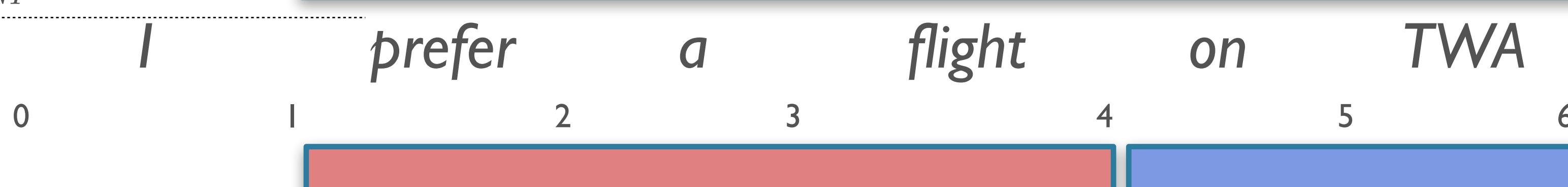
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NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	
	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,4]		<b>VP, X2, S</b> [1,6]
		<b>Det</b> [1,3]	<b>NP</b> [2,4]		<b>NP</b> [2,6]
				<b>[2,5]</b>	
			<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
				<b>[3,5]</b>	
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$Det \rightarrow that | this | a$

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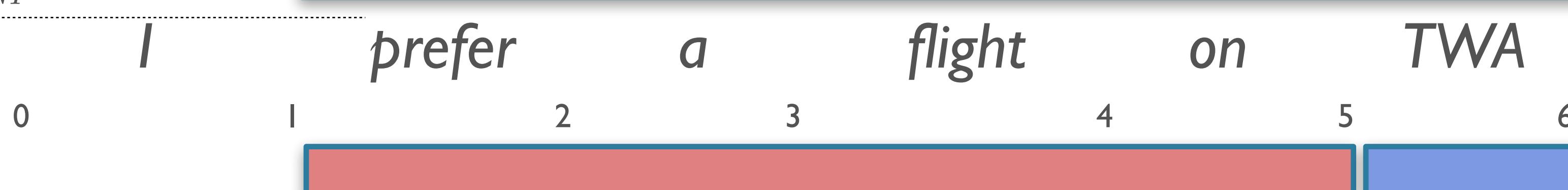
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$Preposition \rightarrow from | to | on | near | through$

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 $S \rightarrow X2 PP$   
 $S \rightarrow Verb PP$   
 $S \rightarrow VP PP$   
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 $NP \rightarrow Det Nominal$   
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 $X2 \rightarrow Verb NP$   
 $VP \rightarrow Verb PP$   
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NP, Pronoun [0,1]	S [0,2]		S [0,3]		S [0,4]		[0,5]	[0,6]
	Verb, VP, S [1,2]		Verb, VP, S [1,3]		VP, X2, S [1,4]		VP, X2, S [1,5]	VP, X2, S [1,6]
		Det		Det	NP		NP	NP
			[2,3]		[2,4]		[2,5]	[2,6]
				Noun, Nom [3,4]			[3,5]	Nom [3,6]
						Prep [4,5]		PP [4,6]
							NNP, NP [5,6]	

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$\mathcal{L}_1$  Grammar

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**NP,  
Pronoun**  
[0,1]

**S**

[0,2]

**S**

[0,3]

**S**

[0,4]

**S**

[0,5]

**S**

[0,6]

**Verb, VP, S**

[1,2]

**Verb**

[1,3]

**Det**

[1,4]

**NP**

[1,5]

**NP**

[1,6]

**VP, X2, S**

[1,4]

**VP**

[1,5]

**Noun, Nom**

[2,4]

**Nom**

[2,5]

**Nom**

[2,6]

**VP, X2, S**

[1,6]

**NP**

[1,6]

**NP**

[3,6]

**PP**

[3,6]

**NNP, NP**

[4,6]

**NNP, NP**

[4,6]

**NNP, NP**

[4,6]

**Lexicon**

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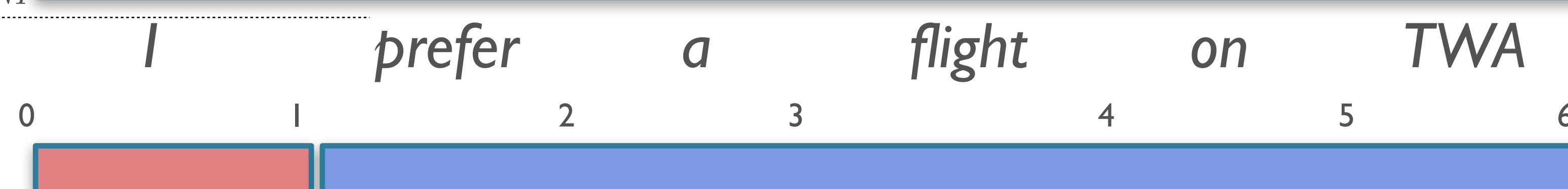
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		<b>Det</b> [2,3]	<b>NP</b> [2,4]		<b>NP</b> [2,6]
			<b>Noun, Nom</b> [3,4]		<b>Nom</b> [3,6]
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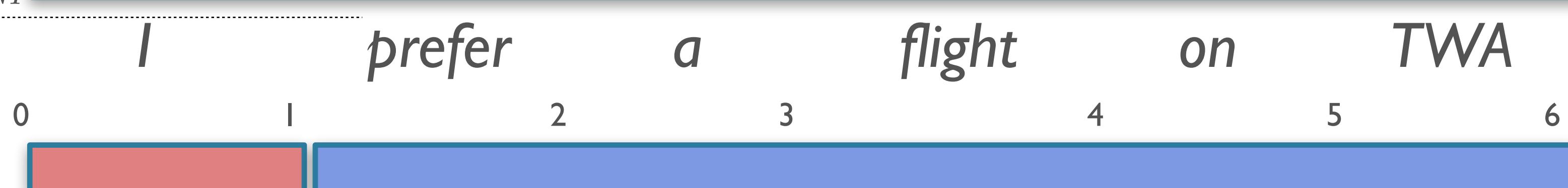
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	<b>Verb, VP, S</b> [1,2]		<b>VP, X2, S</b> [1,3]		<b>VP, X2, S</b> [1,6]
		<b>Det</b> [2,3]	<b>NP</b> [1,4]	<b>NP</b> [1,5]	<b>NP</b> [2,6]
			<b>Noun, Nom</b> [2,4]		<b>Nom</b> [3,6]
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NP, Pronoun [0,1]	S [0,2]		S [0,3]	S [0,4]		S [0,6]
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			Det [2,3]	NP [2,4]		NP [2,6]
				Noun, Nom [3,4]		Nom [3,6]
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**Lexicon**

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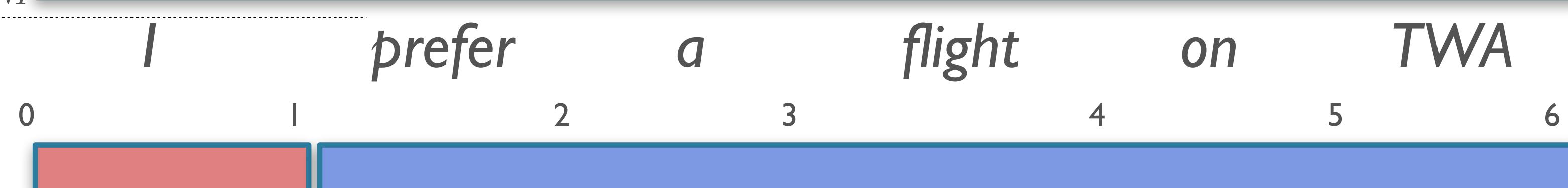
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NP, Pronoun [0,1]	S [0,2]	[0,3]	S [0,4]	[0,5]	S [0,6]
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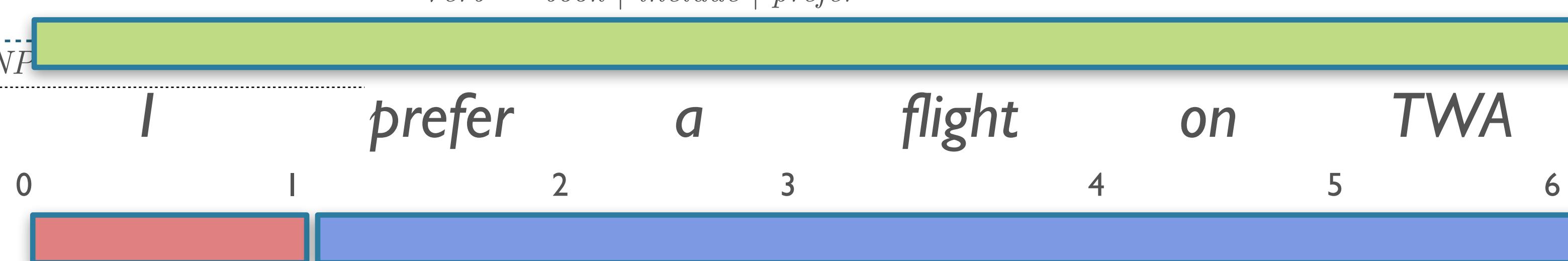
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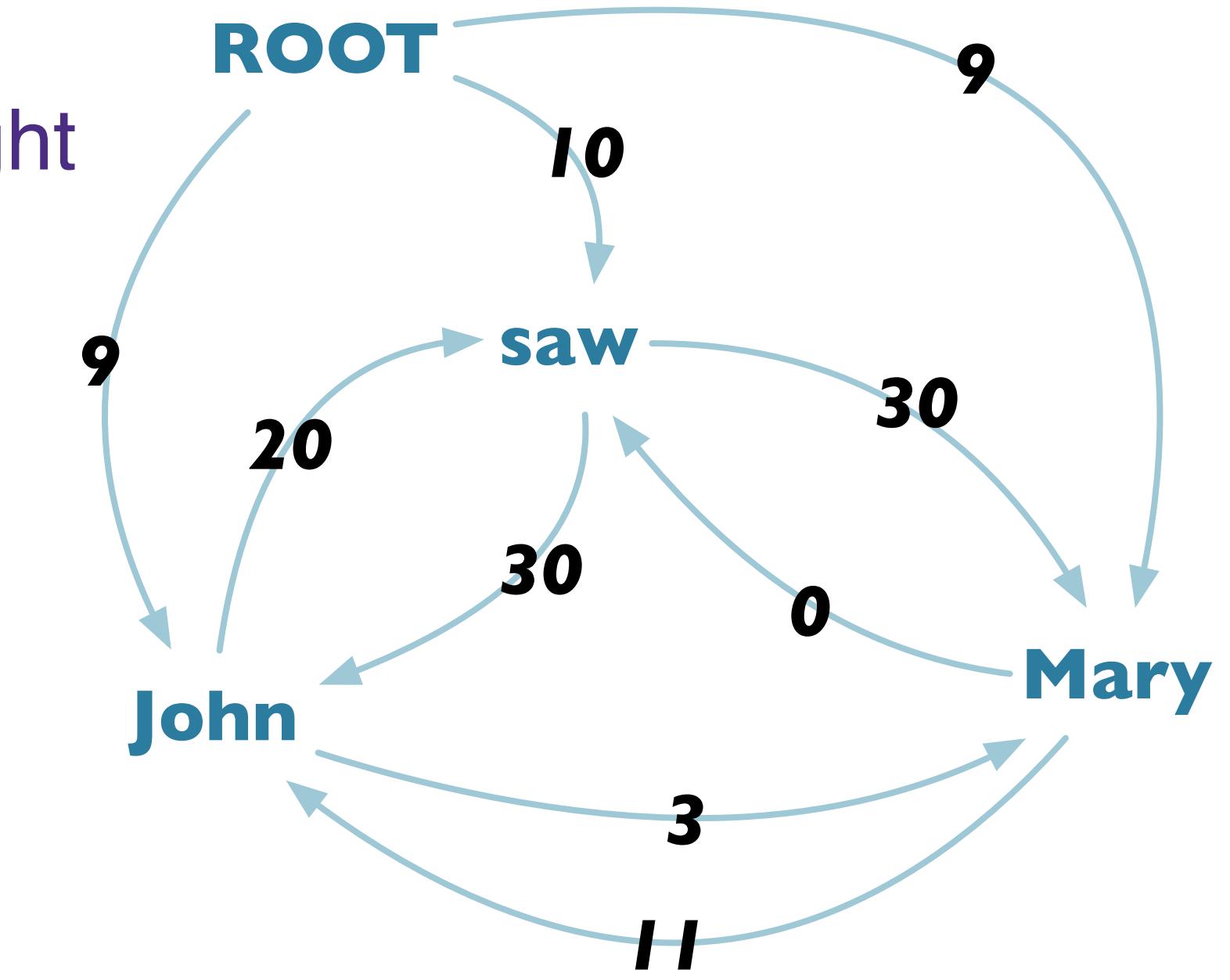
$Preposition \rightarrow from | to | on | near | through$

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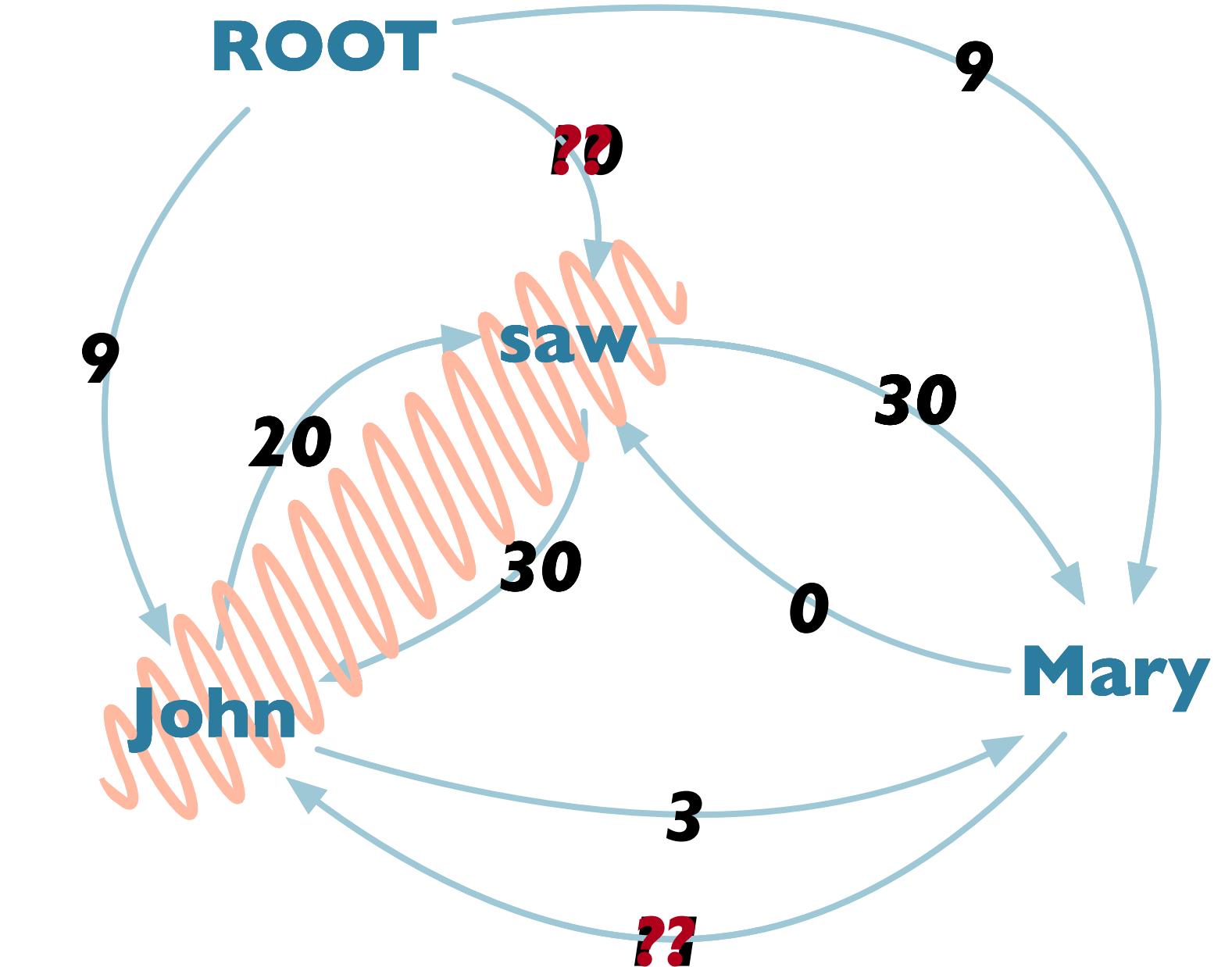
# Maximum Spanning Tree

- McDonald et al, 2005 use variant of Chu-Liu-Edmonds algorithm for MST (CLE)
- Sketch of algorithm:
  - For each node, greedily select incoming arc with max weight
  - If the resulting set of arcs forms a tree, this is the MST.
  - If not, there must be a cycle.
    - “Contract” the cycle: Treat it as a single vertex
    - Recalculate weights into/out of the new vertex
    - Recursively do MST algorithm on resulting graph
- Running time: naïve:  $O(n^3)$ ; Tarjan:  $O(n^2)$
- Applicable to non-projective graphs



# Step 1 & 2

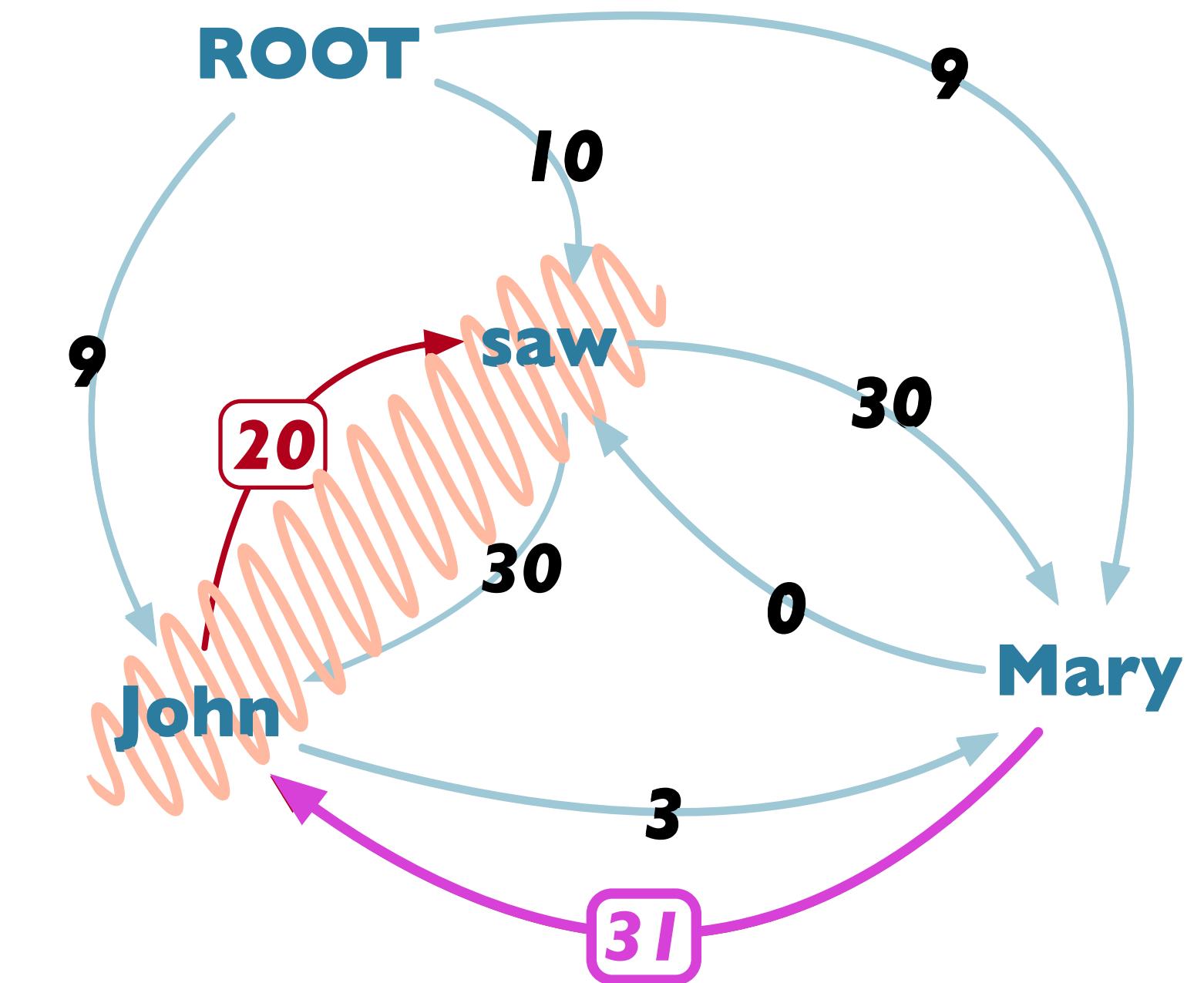
- Find, for each word, the highest scoring incoming edge.
- Is it a tree?
- No, there's a cycle.
- Collapse the cycle
- And re-examine the edges again



# Calculating Weights for Collapsed Vertex

- Since there's a cycle:
  - Contract cycle & reweight
  - John+saw as single vertex
  - Calculate weights in & out as:
- Recurse

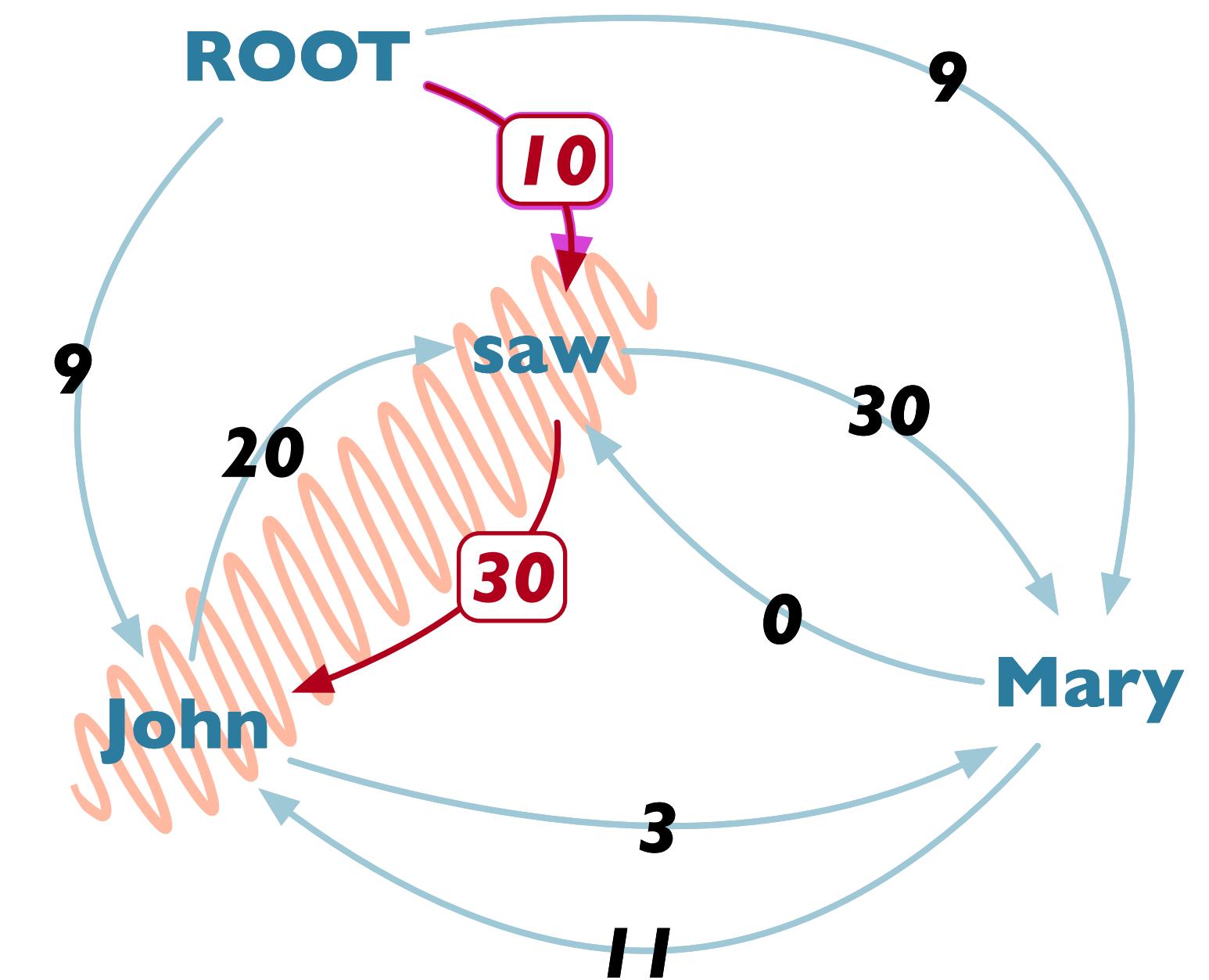
$$s(\text{ Mary}, \mathcal{C}) \amalg + 20 = 31$$



# Calculating Weights for Collapsed Vertex

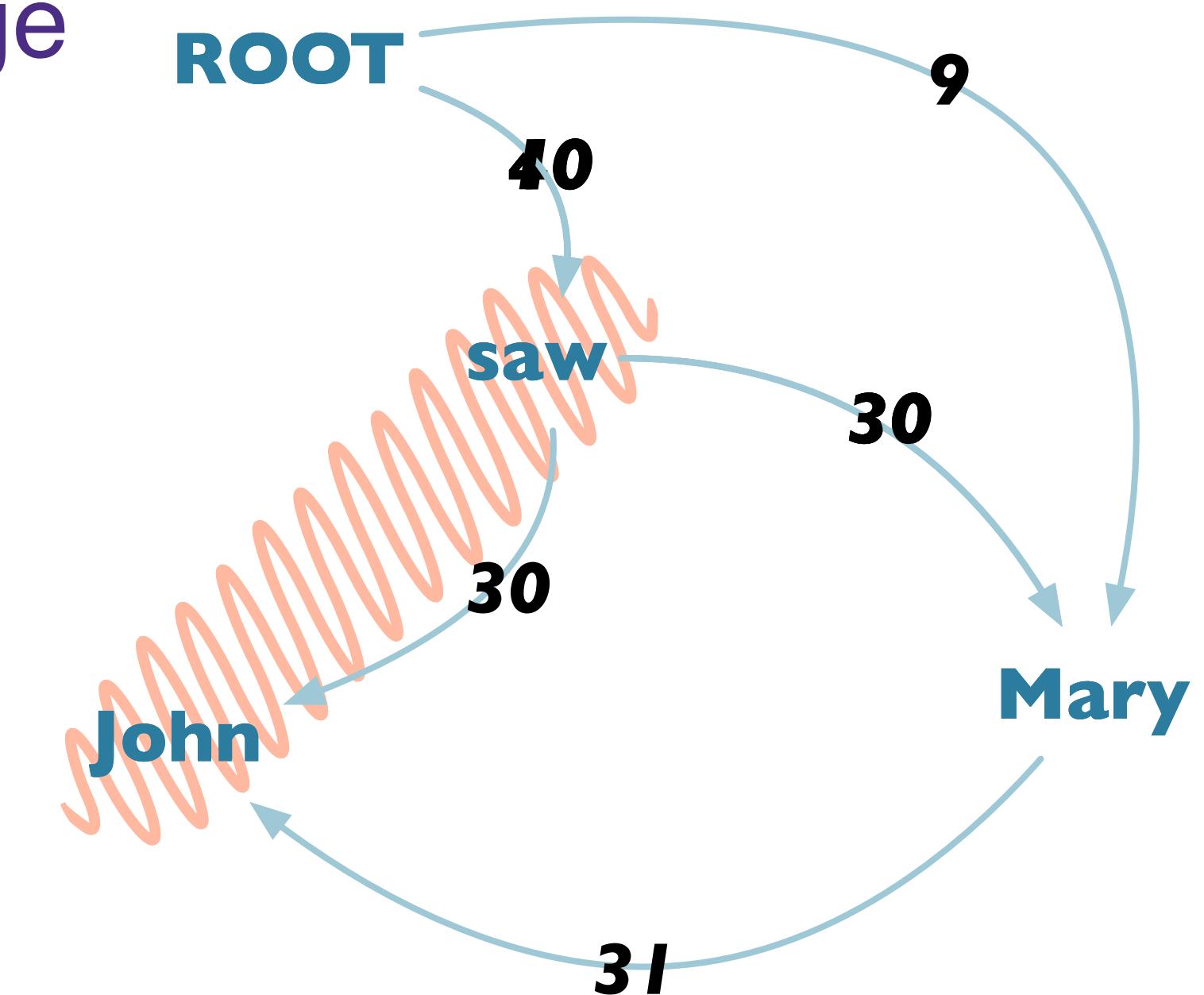
- Since there's a cycle:
  - Contract cycle & reweight
  - John+saw as single vertex
  - Calculate weights in & out as:
- Recurse

$$s(\text{ROOT}, C) \mid 0 + 30 = 40$$



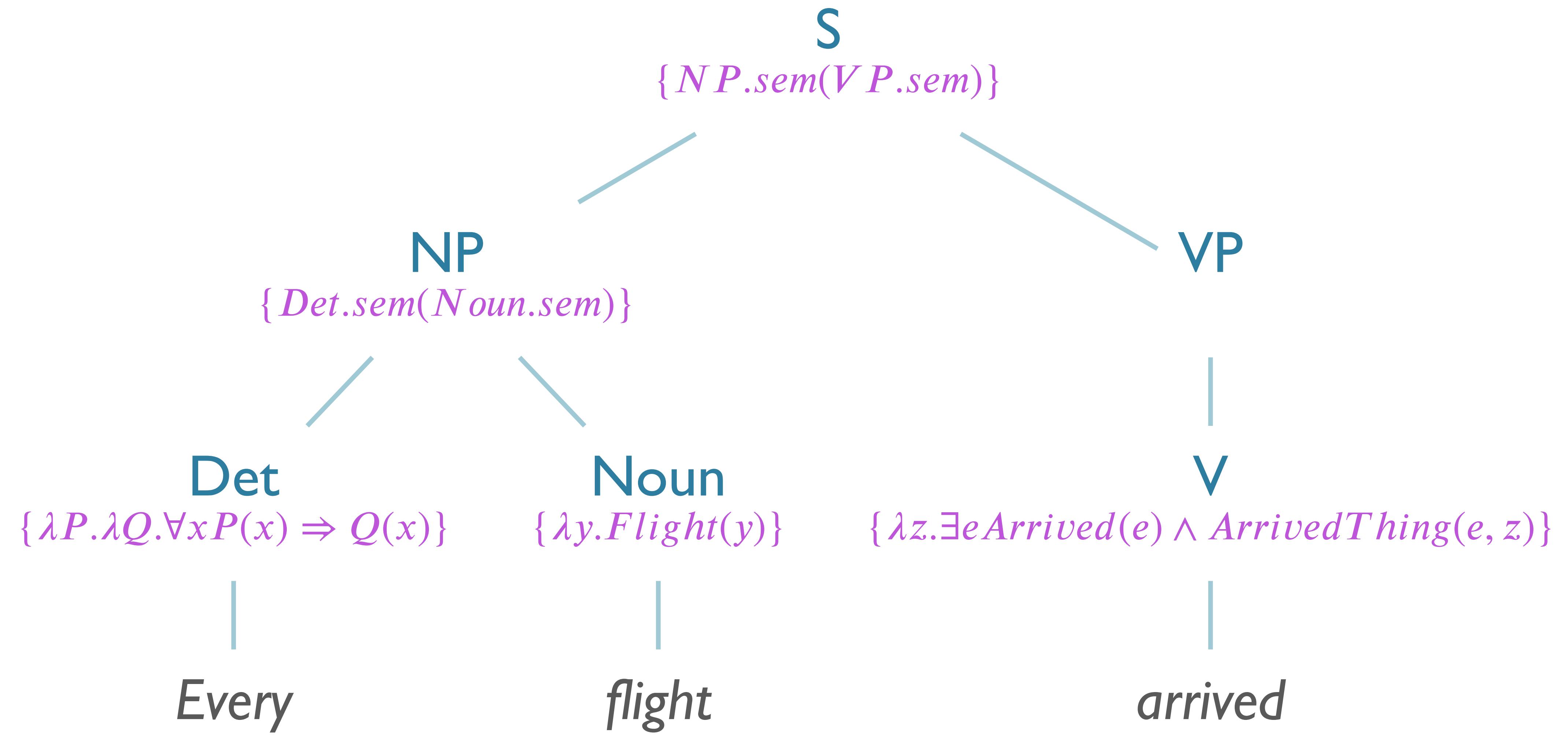
# Step 3

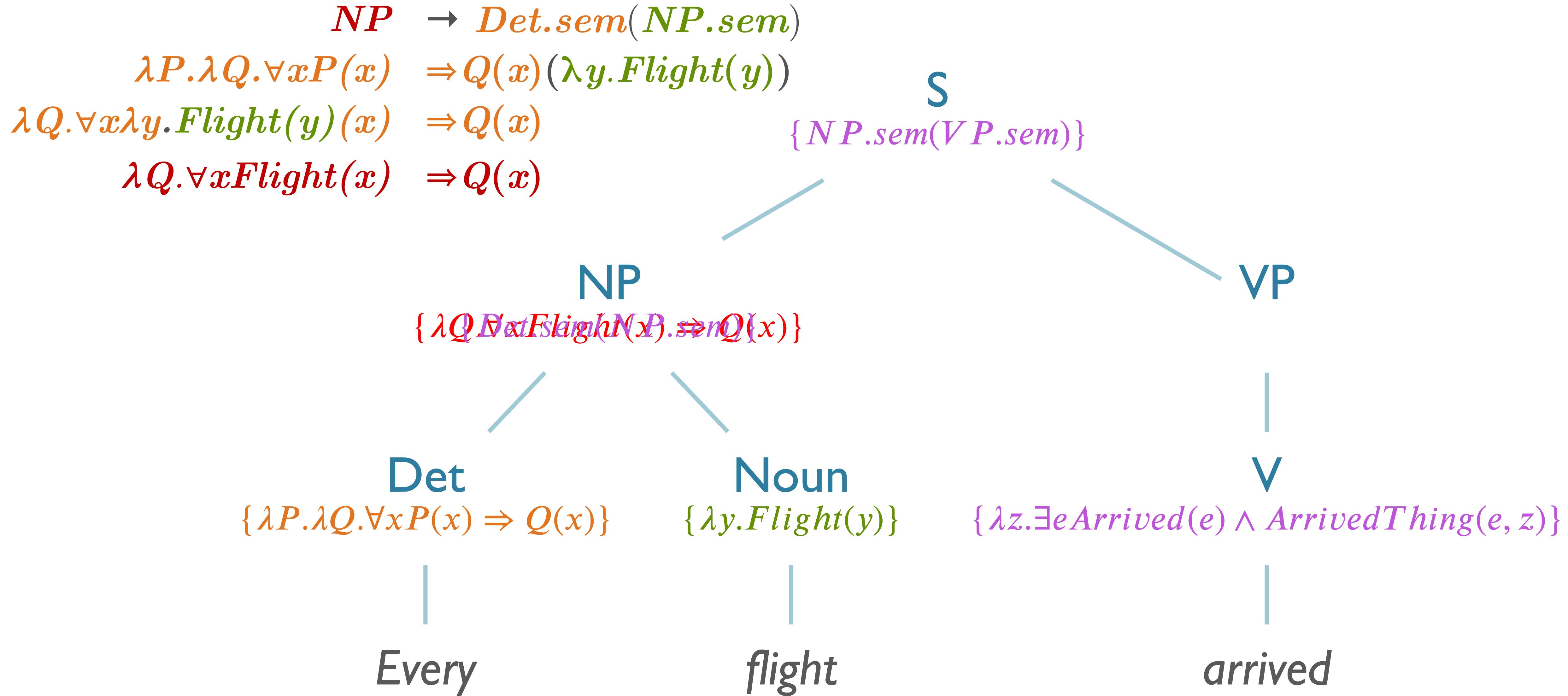
- With cycle collapsed, recurse on step 1:
- Keep highest weighted incoming edge for each edge
- Is it a tree?
- Yes!
- ...but must recover collapsed portions.

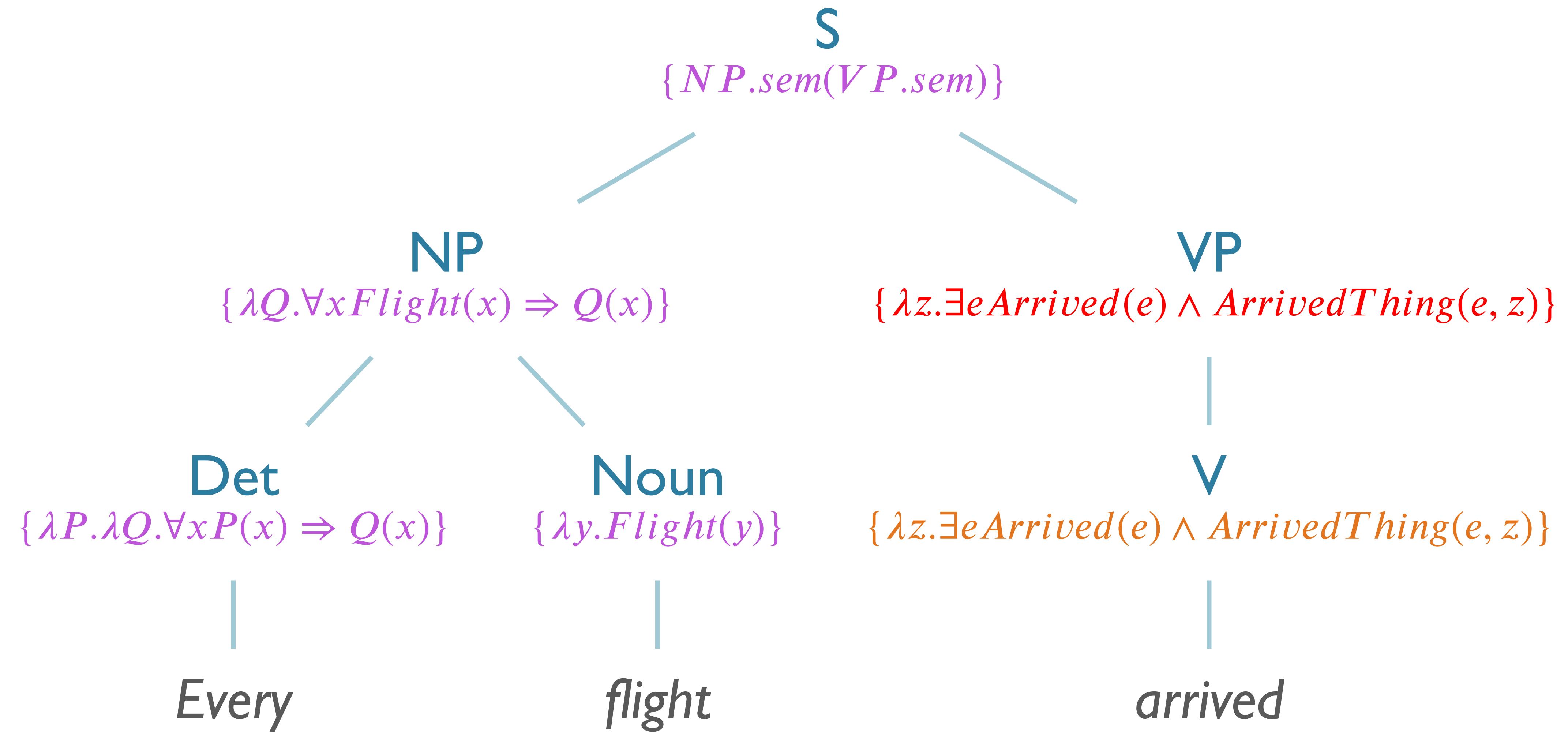


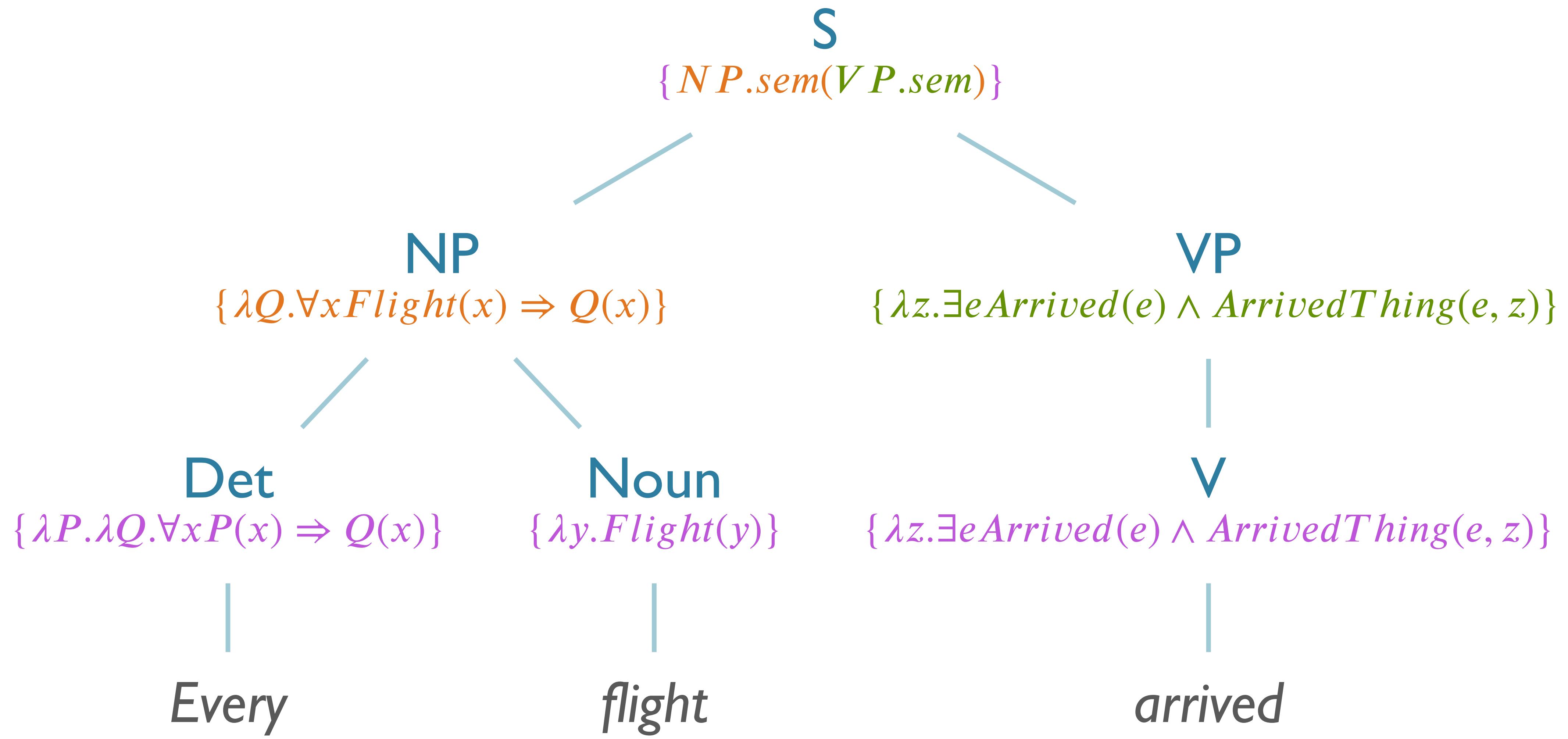
# Semantics

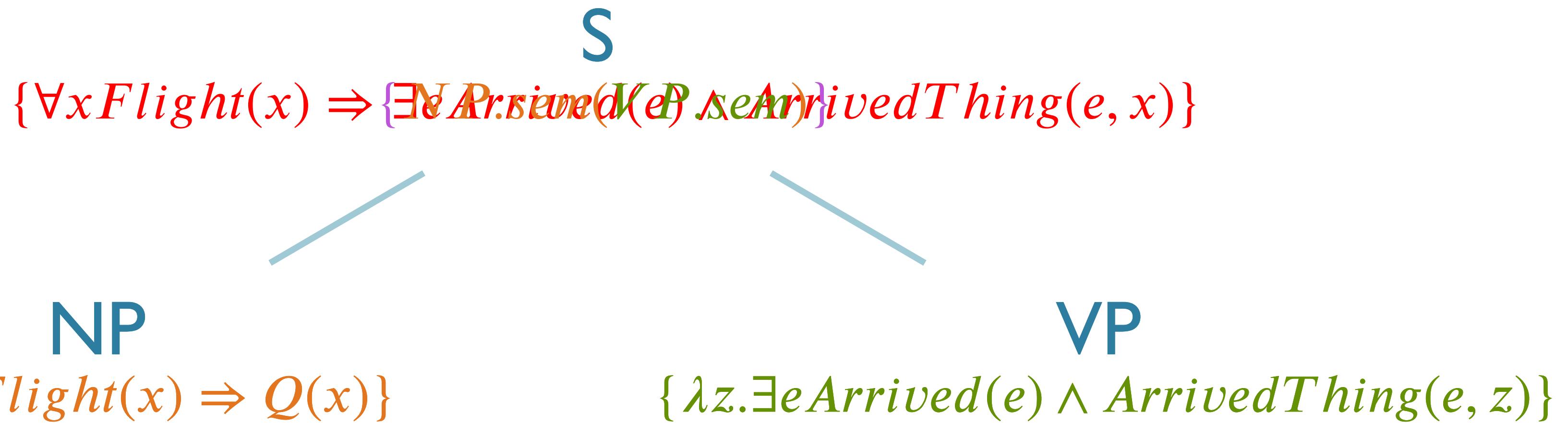
- First order logic + lambda calculus
- Neo-Davidsonian event semantics
- Parsing via features
- Distributional Semantics + word embeddings
- Word Sense Disambiguation
- Semantic Role Labeling







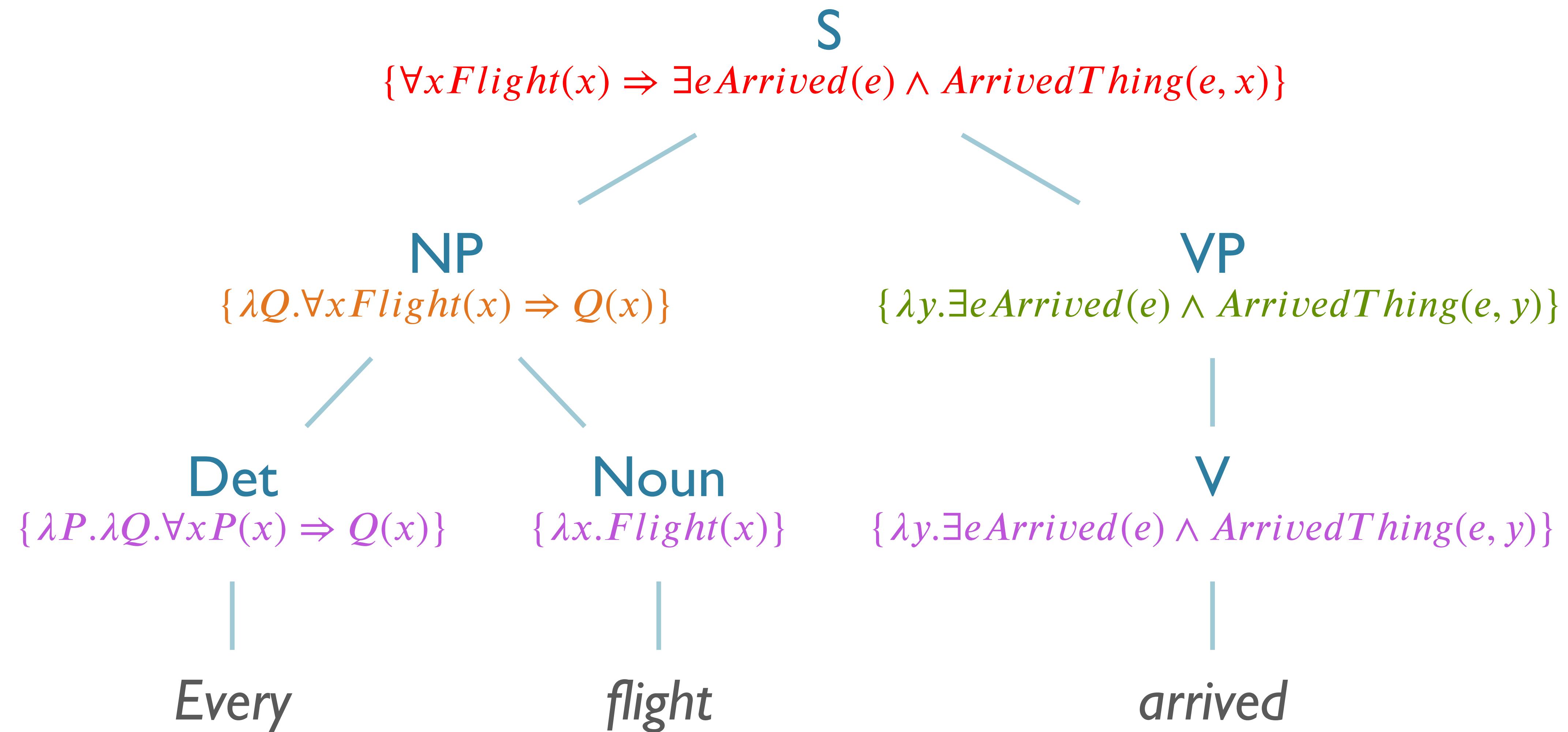




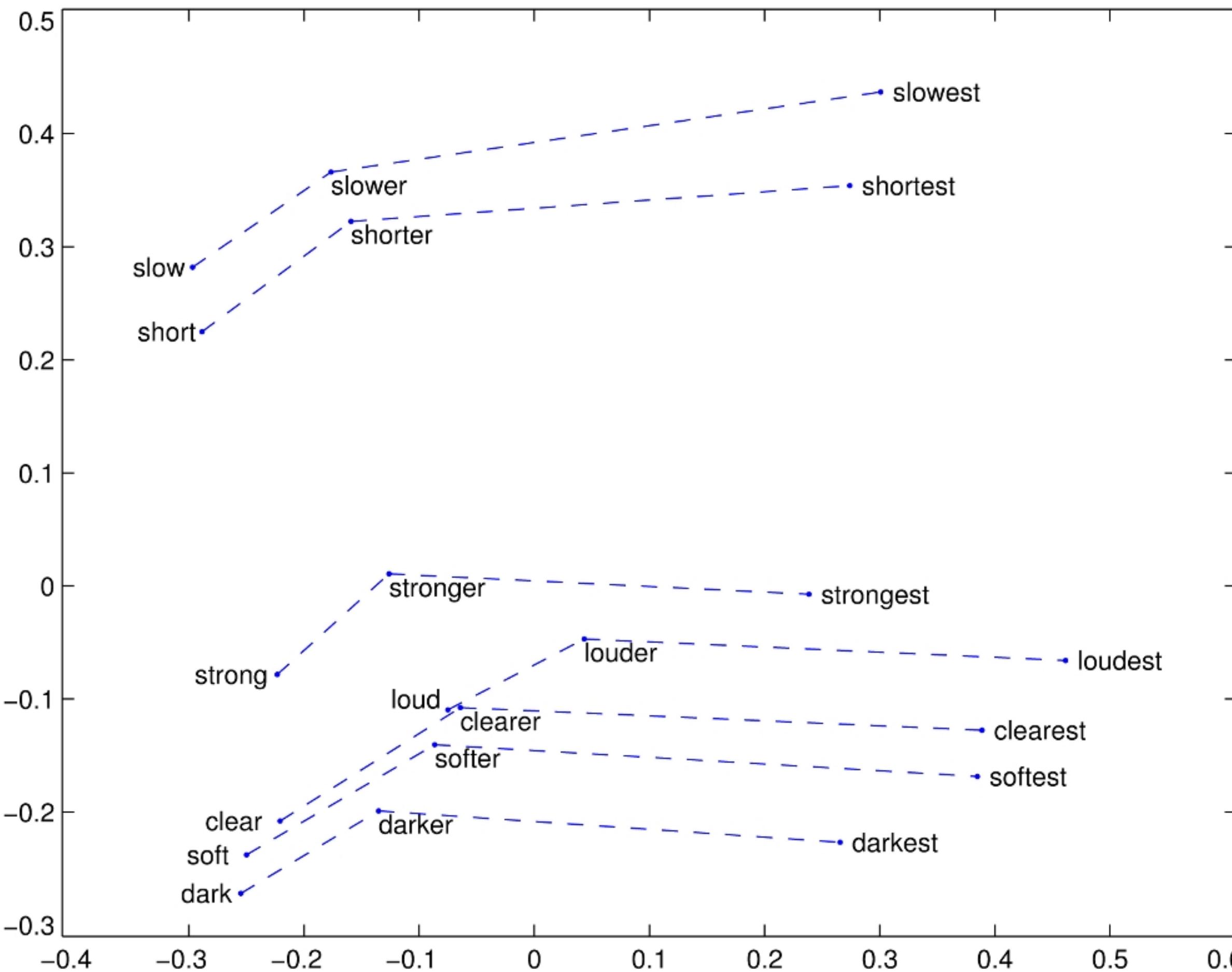
$\lambda Q. \forall x Flight(x) \Rightarrow Q(x) (\lambda z. \exists e Arrived(e) \wedge ArrivedThing(e, z))$

$\forall x Flight(x) \Rightarrow \lambda z. \exists e Arrived(e) \wedge ArrivedThing(e, z)(x)$

$\forall x Flight(x) \Rightarrow \exists e Arrived(e) \wedge ArrivedThing(e, x)$



# Word Vectors



# Pragmatics

- Discourse phenomena
- Coreference resolution [esp. pronominal]
  - Hobbs' Algorithm
- Segmentation / Cohesion
- Discourse parsing: hierarchical structure of coherence relations

# Summary

- Deep Processing techniques for NLP
  - Parsing, semantic analysis, logical forms, reference, etc
  - Create richer computational models of natural language
    - Closer to language understanding
- Shallow processing techniques have dominated many areas
  - IR, QA, MT, WSD, etc
  - More computationally tractable, fewer required resources
- Deep processing techniques experience resurgence
  - Some big wins – e.g. QA
  - Improved resources: treebanks (syntactic/discourse, FrameNet, Propbank)
  - Improved learning algorithms: structured learners, neural nets
  - Increased computation: cloud resources, Grid, etc
  - Current goal: leveraging these resources to do deep processing [e.g. semi-supervised learning]

# Thank you!

Course evaluations:  
<http://bit.ly/571-aut19-eval>