Natural Language Processing with Deep Learning

CS224N/Ling284

Diyi Yang

Lecture 4: Dependency Parsing

Lecture Plan

Finish backpropagation (10 mins)

Syntactic Structure and Dependency parsing

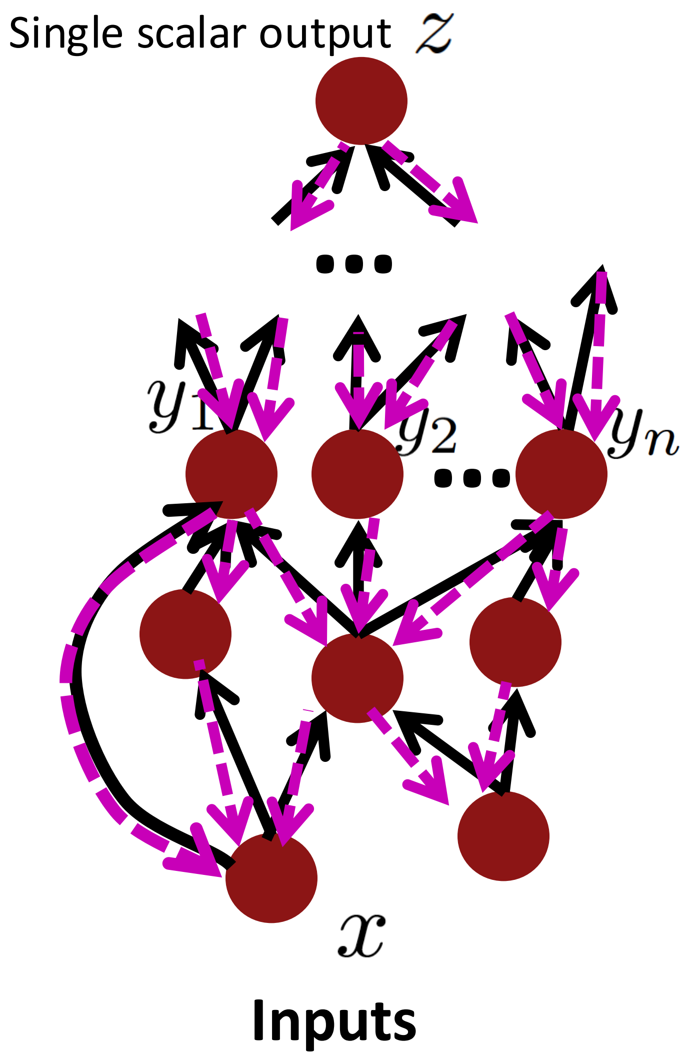
1. Syntactic Structure: Consistency and Dependency (20 mins)
2. Dependency Grammar and Treebanks (15 mins)
3. Transition-based dependency parsing (15 mins)
4. Neural dependency parsing (20 mins)

Key Learnings: Explicit linguistic structure and how a neural net can decide it

Reminders/comments:

- In Assignment 2, you build a neural dependency parser using PyTorch!
- Come to the PyTorch tutorial, Friday, 1:30pm Gates B01
- Final project discussions – **come meet with us**; focus of Tuesday class in week 4

Back-Prop in General Computation Graph



1. Fprop: visit nodes in topological sort order
    - Compute value of node given predecessors
2. Bprop:
    - initialize output gradient = 1
    - visit nodes in reverse order:
    Compute gradient wrt each node using gradient wrt successors

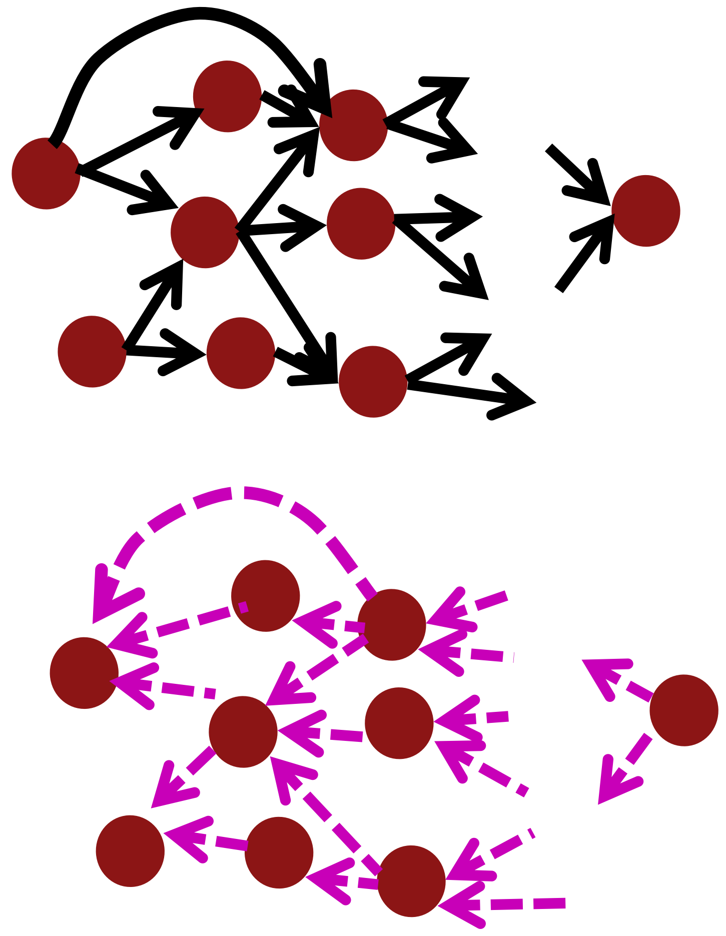
$\{y_1, y_2, \ldots y_n\}$ = successors of x

$$\frac{\partial z}{\partial x} = \sum_{i=1}^{n} \frac{\partial z}{\partial y_i} \frac{\partial y_i}{\partial x}$$

Done correctly, big O() complexity of fprop and bprop is **the same**

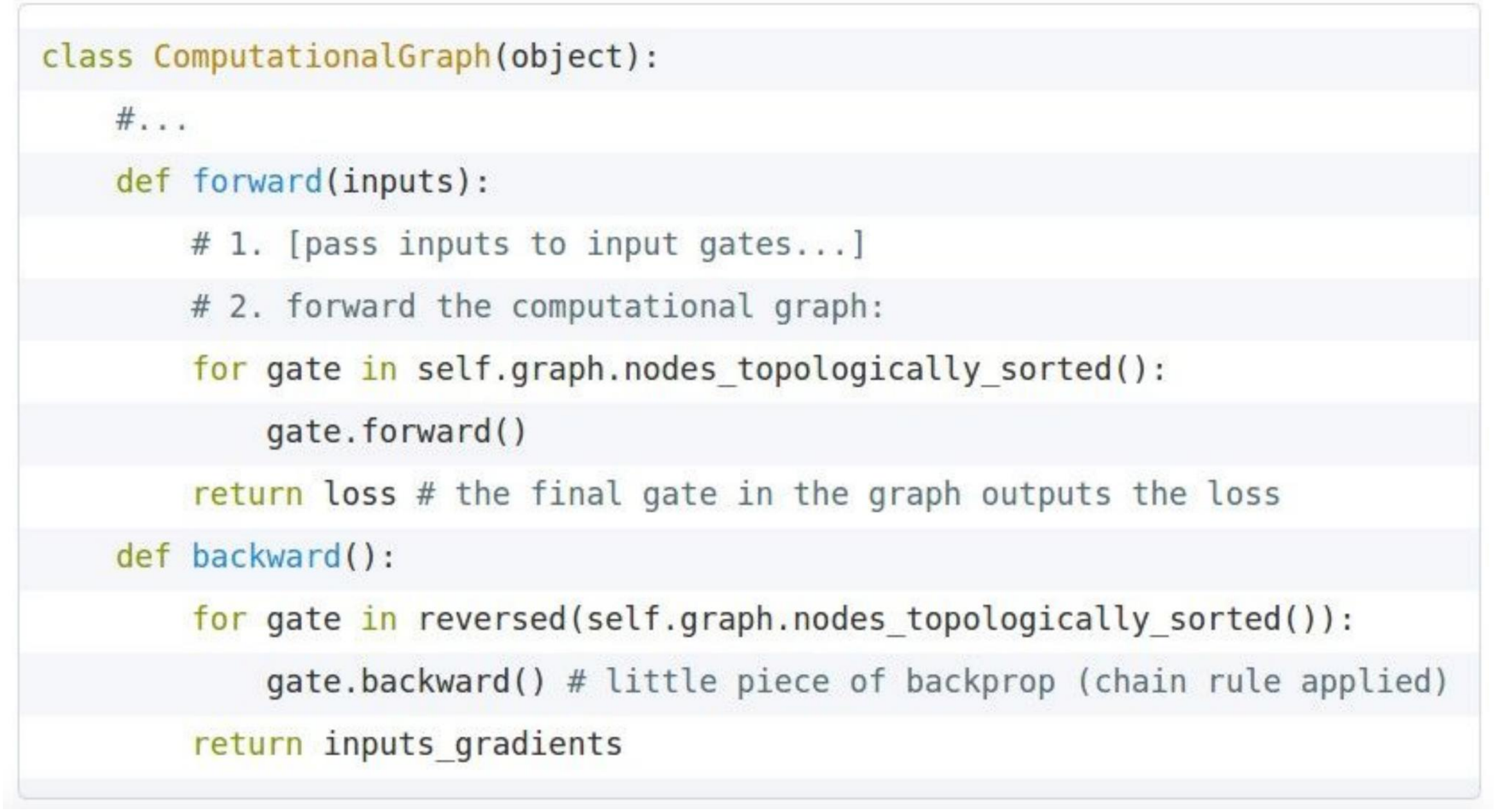
In general, our nets have regular layer-structure and so we can use matrices and Jacobians…

Automatic Differentiation



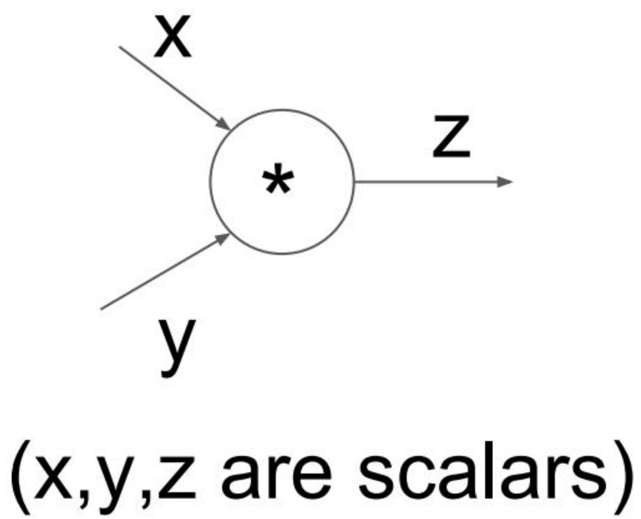
- The gradient computation can be automatically inferred from the symbolic expression of the fprop
- Each node type needs to know how to compute its output and how to compute the gradient wrt its inputs given the gradient wrt its output
- Modern DL frameworks (Tensorflow, PyTorch, etc.) do backpropagation for you but mainly leave layer/node writer to hand-calculate the local derivative

Backprop Implementations

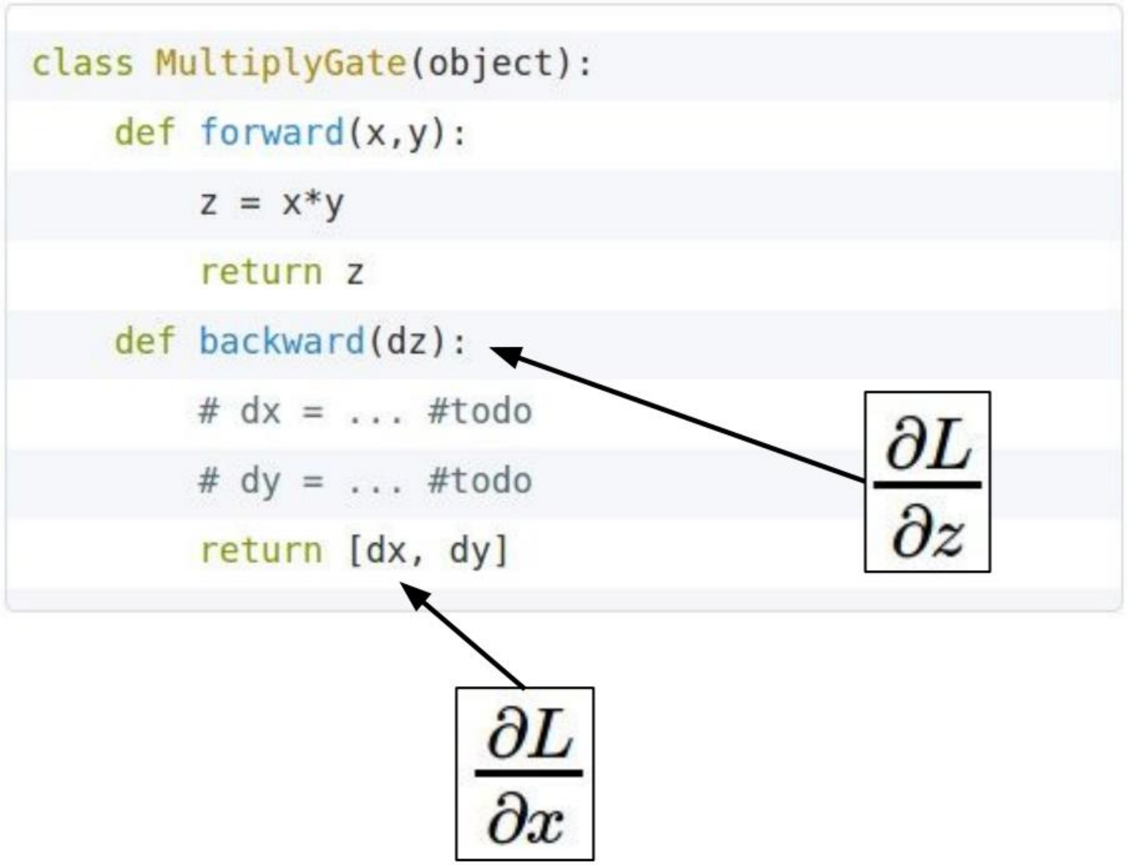


```python
class ComputationalGraph(object):
    #...
    def forward(inputs):
        # 1. [pass inputs to input gates...]
        # 2. forward the computational graph:
        for gate in self.graph.nodes_topologically_sorted():
            gate.forward()
        return loss # the final gate in the graph outputs the loss
    def backward():
        for gate in reversed(self.graph.nodes_topologically_sorted()):
            gate.backward() # little piece of backprop (chain rule applied)
        return inputs_gradients
```

Implementation: forward/backward API



(x,y,z are scalars)

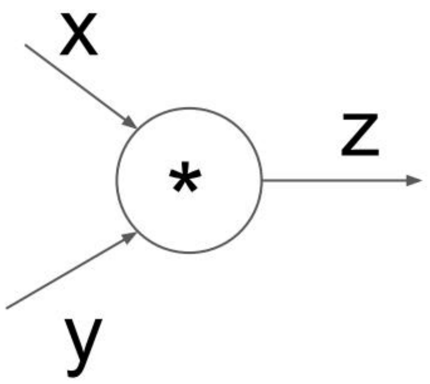


```
class MultiplyGate(object):
    def forward(x,y):
        z = x*y
        return z
    def backward(dz):
        # dx = ... #todo
        # dy = ... #todo
        return [dx, dy]
```

$\boxed{\frac{\partial L}{\partial z}}$

$\boxed{\frac{\partial L}{\partial x}}$

Implementation: forward/backward API



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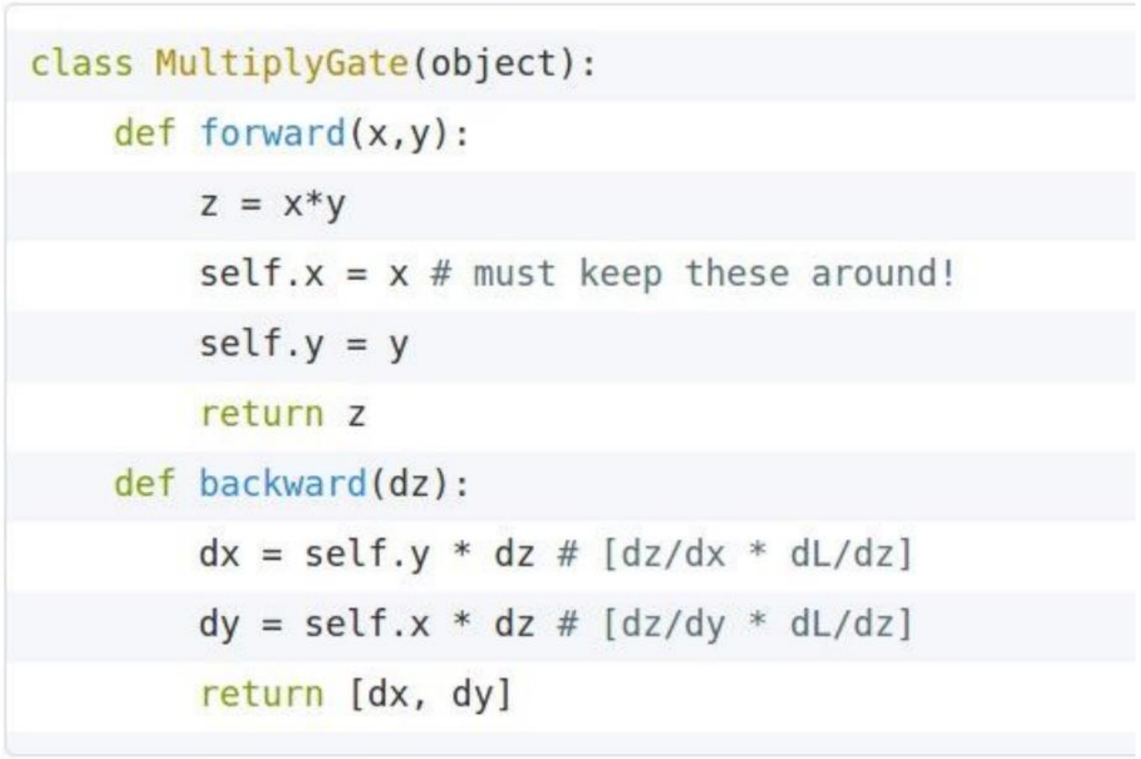

```
class MultiplyGate(object):
    def forward(x,y):
        z = x*y
        self.x = x # must keep these around!
        self.y = y
        return z
    def backward(dz):
        dx = self.y * dz # [dz/dx * dL/dz]
        dy = self.x * dz # [dz/dy * dL/dz]
        return [dx, dy]
```

Manual Gradient checking: Numeric Gradient

- For small *h* (≈ 1e-4),

$$f'(x) \approx \frac{f(x+h) - f(x-h)}{2h}$$

- Easy to implement correctly
- But approximate and **very** slow:
  - You have to recompute *f* for **every parameter** of our model
- Useful for checking your implementation
  - In the old days, we hand-wrote everything, doing this everywhere was the key test
  - Now much less needed; you can use it to check layers are correctly implemented

Summary

We've mastered the core technology of neural nets! 🎉 🎉 🎉

- **Backpropagation:** recursively (and hence efficiently) apply the chain rule along computation graph
  - [downstream gradient] = [upstream gradient] x [local gradient]
- **Forward pass:** compute results of operations and save intermediate values
- **Backward pass:** apply chain rule to compute gradients

Why learn all these details about gradients?

- **Modern deep learning frameworks compute gradients for you!**
  - Come to the PyTorch introduction this Friday!

- But why take a class on compilers or systems when they are implemented for you?
  - Understanding what is going on under the hood is useful!

- Backpropagation doesn't always work perfectly out of the box
  - Understanding why is crucial for debugging and improving models
  - See Karpathy article (in syllabus):
    - https://medium.com/@karpathy/yes-you-should-understand-backprop-e2f06eab496b
  - Example in future lecture: exploding and vanishing gradients

Lecture Plan

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1. The linguistic structure of sentences – two views: Constituency = phrase structure grammar = context-free grammars (CFGs)

Phrase structure organizes words into nested constituents

Starting unit: words

the,   cat,   cuddly,   by,   door

Words combine into phrases

the cuddly cat,   by the door

Phrases can combine into bigger phrases

the cuddly cat by the door

The linguistic structure of sentences – two views: Constituency = phrase structure grammar = context-free grammars (CFGs)

Phrase structure organizes words into nested constituents.

the cat

a dog

large in a crate

barking on the table

cuddly by the door

large barking

talk to

walked behind

Two views of linguistic structure: Dependency structure

- Dependency structure shows which words depend on (modify, attach to, or are arguments of) which other words.

Look in the large crate in the kitchen by the door

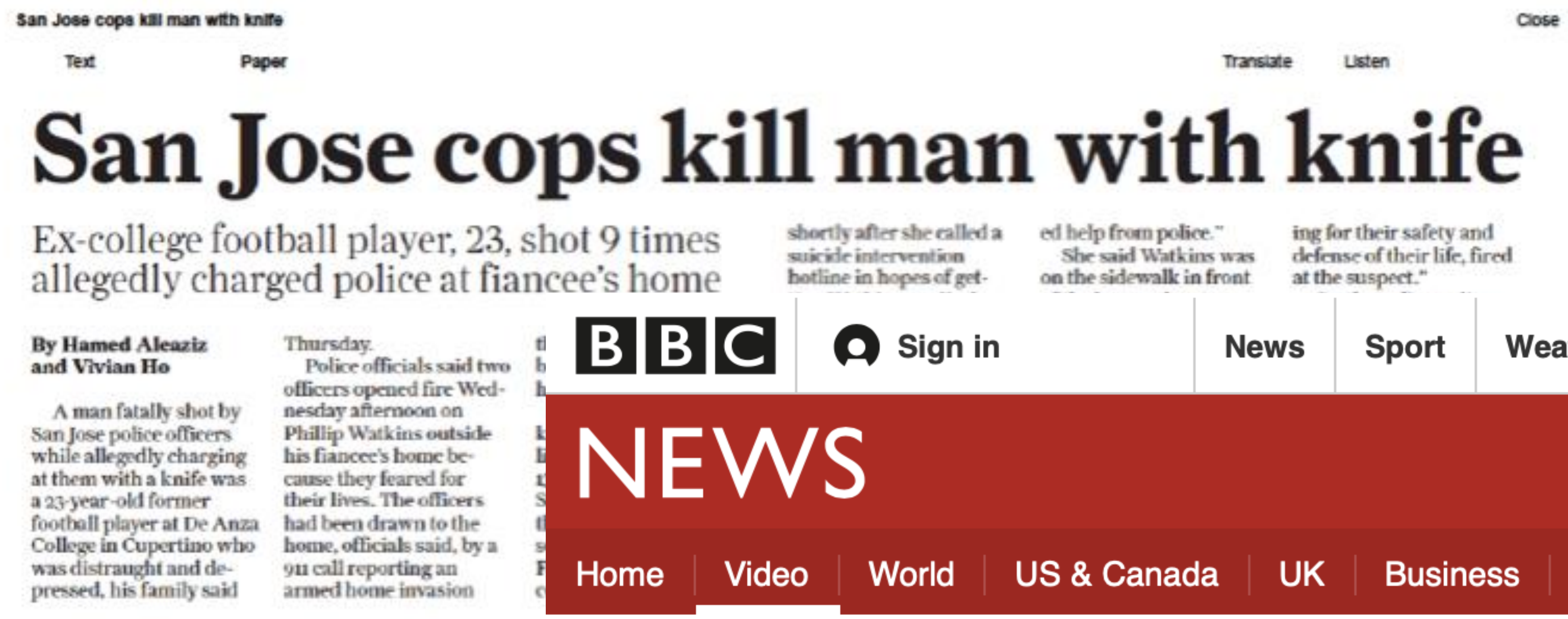
Why do we need sentence structure?

Humans communicate complex ideas by composing words together into bigger units to convey complex meanings

Human listeners need to work out what modifies [attaches to] what

A model needs to understand sentence structure in order to be able to interpret language correctly

Prepositional phrase attachment ambiguity



San Jose cops kill man with knife

Close

Text Paper Translate Listen

San Jose cops kill man with knife

Ex-college football player, 23, shot 9 times allegedly charged police at fiancee's home

By Hamed Aleaziz and Vivian Ho

A man fatally shot by San Jose police officers while allegedly charging at them with a knife was a 23-year-old former football player at De Anza College in Cupertino who was distraught and depressed, his family said

Thursday.

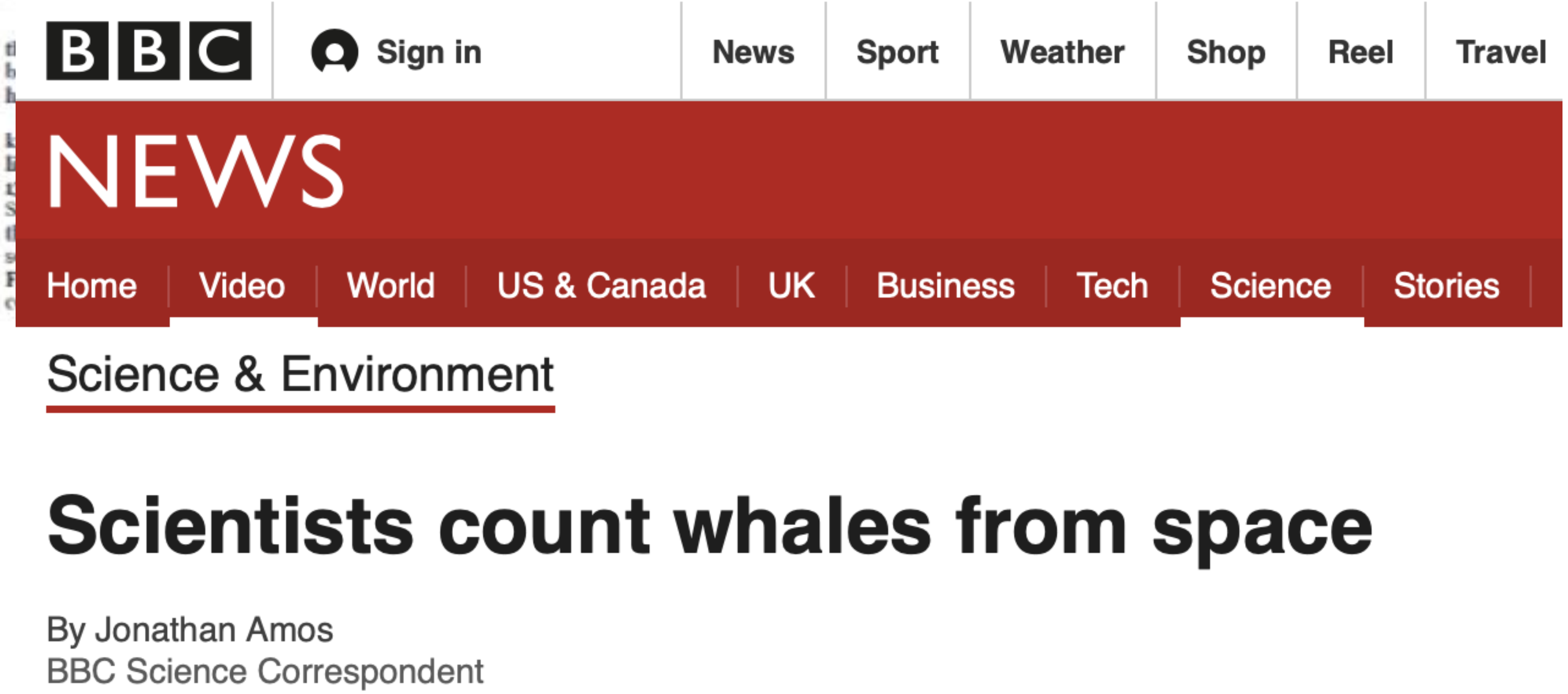
Police officials said two officers opened fire Wednesday afternoon on Phillip Watkins outside his fiancee's home because they feared for their lives. The officers had been drawn to the home, officials said, by a 911 call reporting an armed home invasion

shortly after she called a suicide intervention hotline in hopes of get-

ed help from police."

She said Watkins was on the sidewalk in front

ing for their safety and defense of their life, fired at the suspect."



Science & Environment

Scientists count whales from space

By Jonathan Amos
BBC Science Correspondent

Prepositional phrase attachment ambiguity

Scientists count whales from space

✓

Scientists count whales from space

✗

PP attachment ambiguities multiply

- A key parsing decision is how we ‘attach’ various constituents
  - PPs, adverbial or participial phrases, infinitives, coordinations, etc.

The board approved [its acquisition] [by Royal Trustco Ltd.]

[of Toronto]

[for $27 a share]

[at its monthly meeting].

- Catalan numbers: $C_n = (2n)!/[(n+1)!n!]$
- An exponentially growing series, which arises in many tree-like contexts:
  - E.g., the number of possible triangulations of a polygon with n+2 sides
    - Turns up in triangulation of probabilistic graphical models (CS228)….

Coordination scope ambiguity

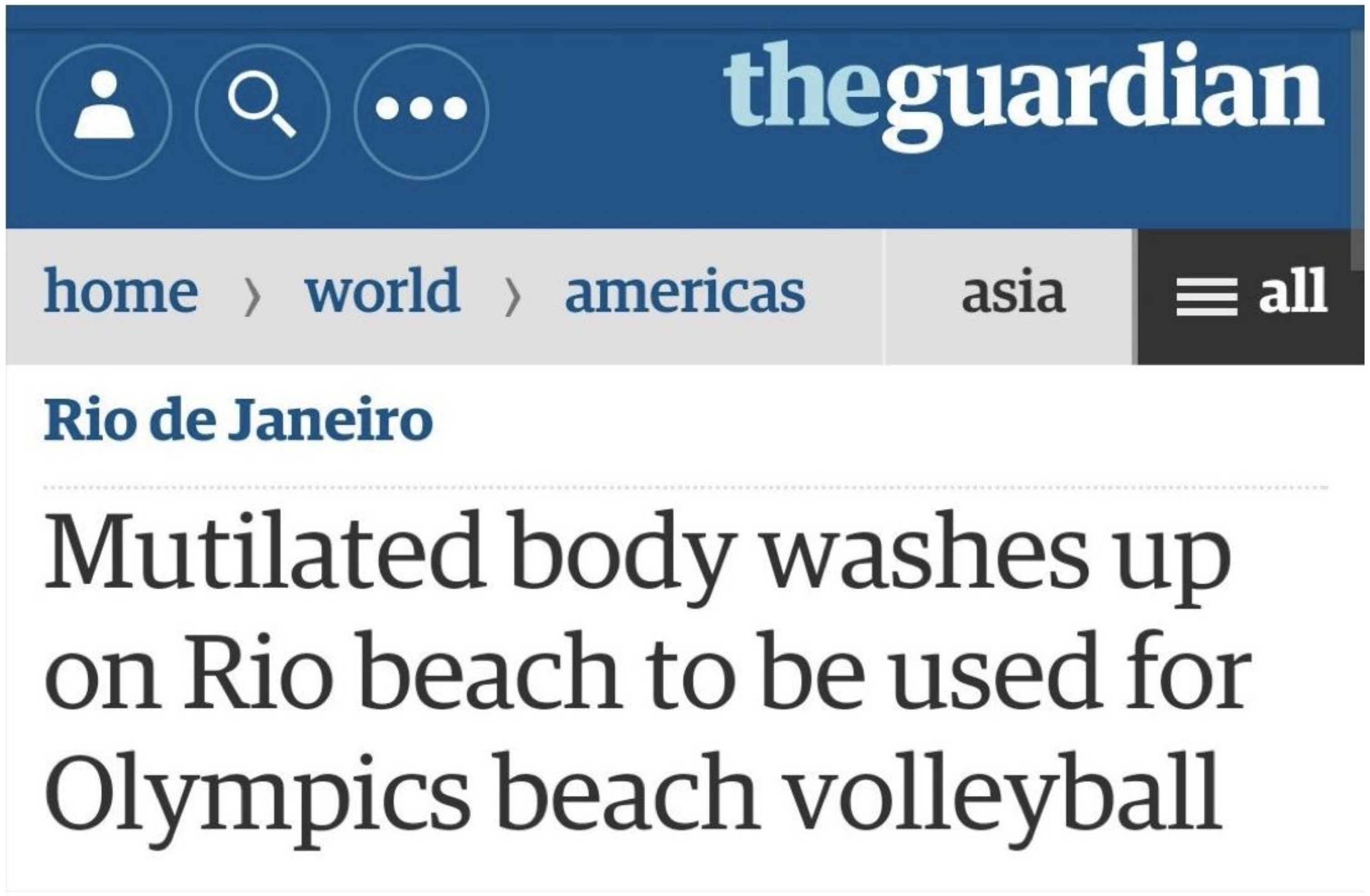
Shuttle veteran and longtime NASA executive Fred Gregory appointed to board

Shuttle veteran and longtime NASA executive Fred Gregory appointed to board

Coordination scope ambiguity

Adjectival/Adverbial Modifier Ambiguity

Verb Phrase (VP) attachment ambiguity

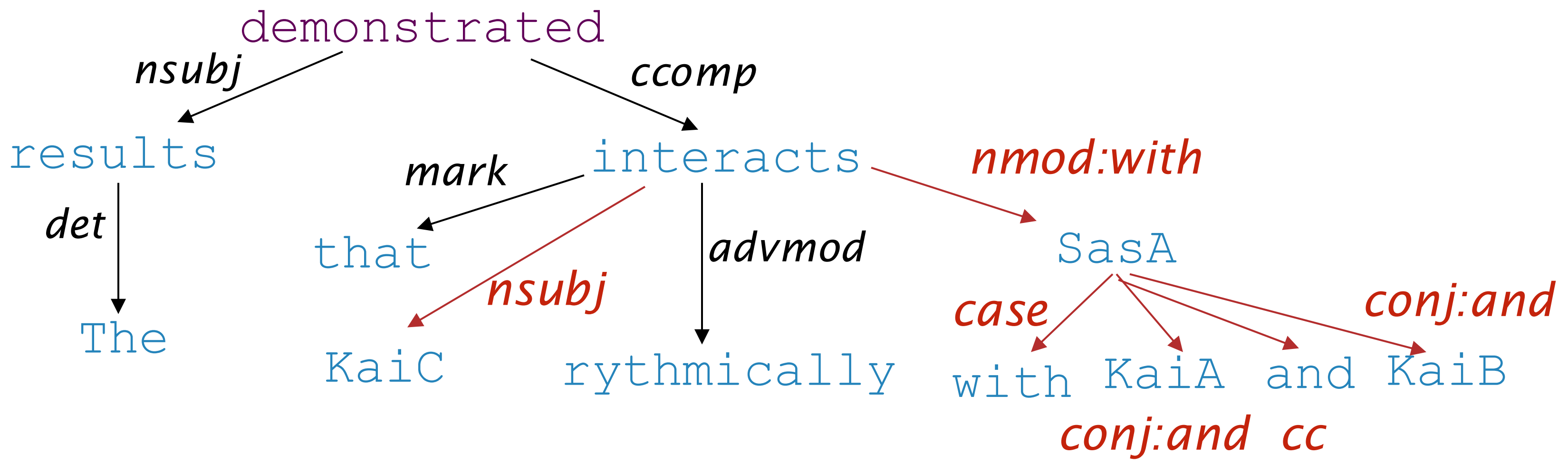


Rio de Janeiro

Mutilated body washes up on Rio beach to be used for Olympics beach volleyball

6/29/16, 1:48 PM

Dependency paths help extract semantic interpretation – simple practical example: extracting protein-protein interaction



KaiC ←nsubj interacts nmod:with → SasA

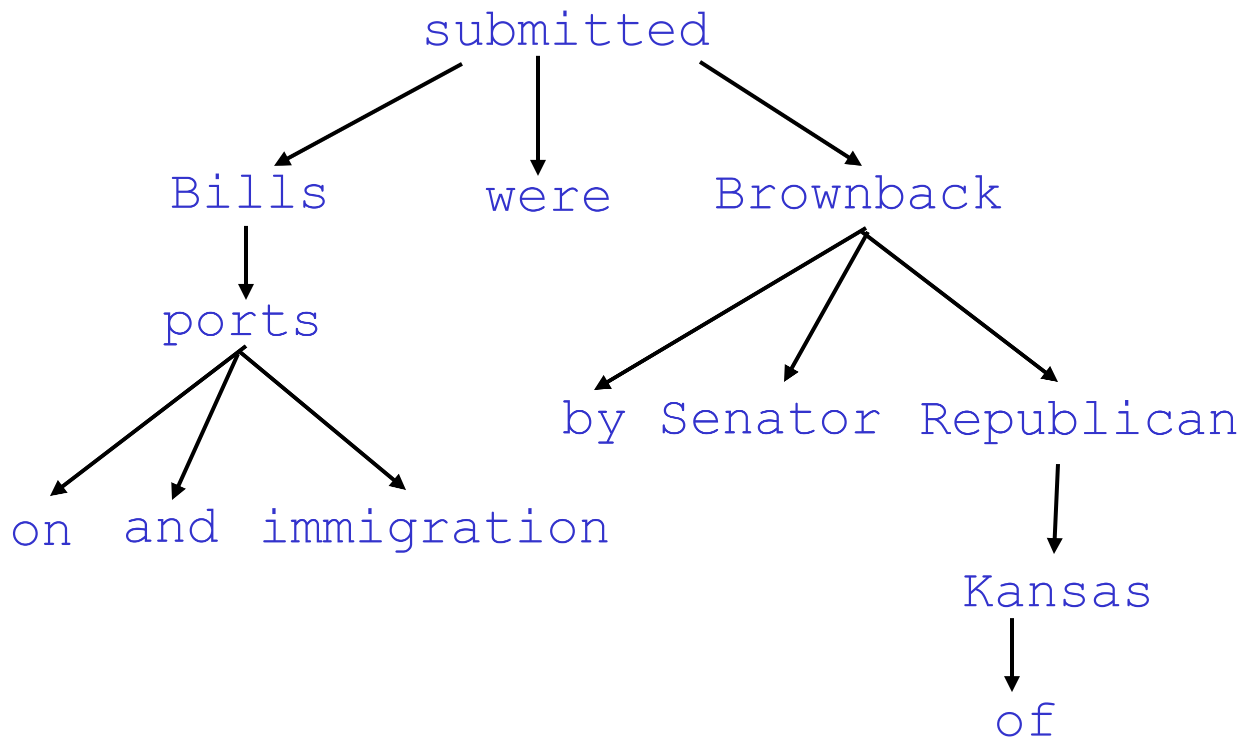
KaiC ←nsubj interacts nmod:with → SasA conj:and→ KaiA

KaiC ←nsubj interacts nmod:with → SasA conj:and→ KaiB

[Erkan et al. EMNLP 07, Fundel et al. 2007, etc.]

2. Dependency Grammar and Dependency Structure

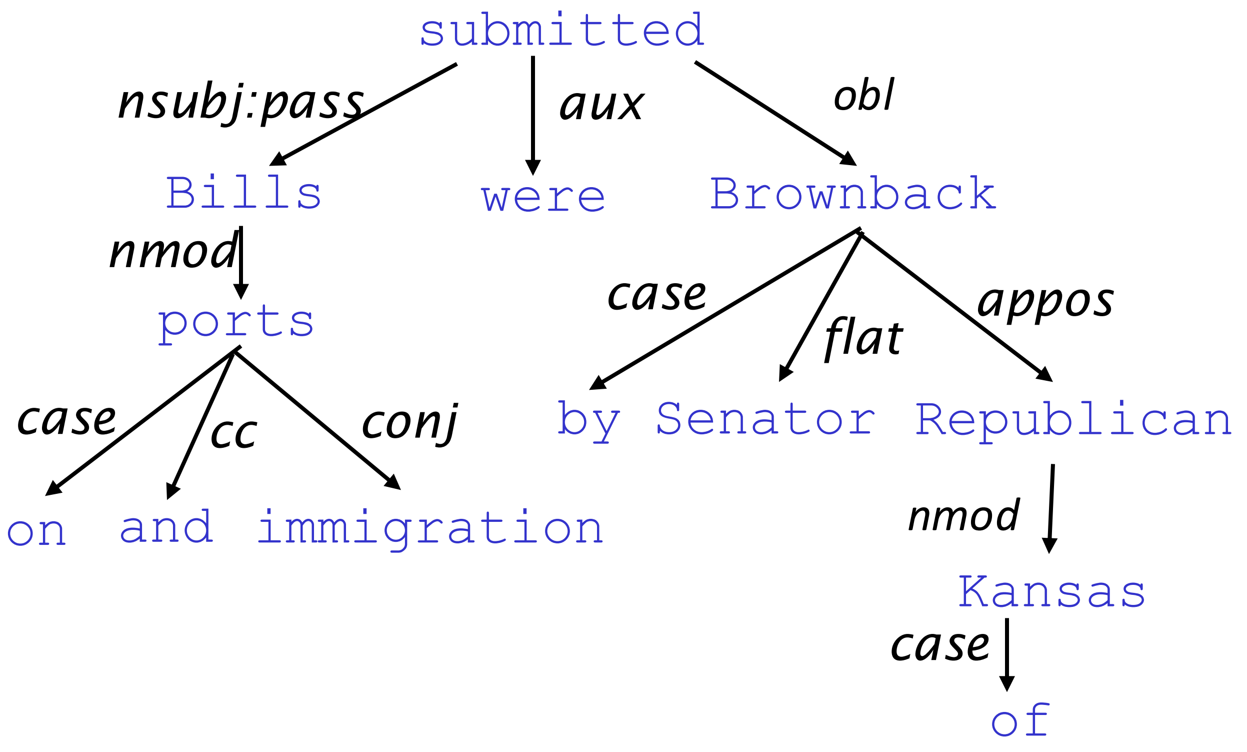
Dependency syntax postulates that syntactic structure consists of relations between lexical items, normally binary asymmetric relations (“arrows”) called dependencies



Dependency Grammar and Dependency Structure

Dependency syntax postulates that syntactic structure consists of relations between lexical items, normally binary asymmetric relations ("arrows") called dependencies

The arrows are commonly typed with the name of grammatical relations (subject, prepositional object, apposition, etc.)

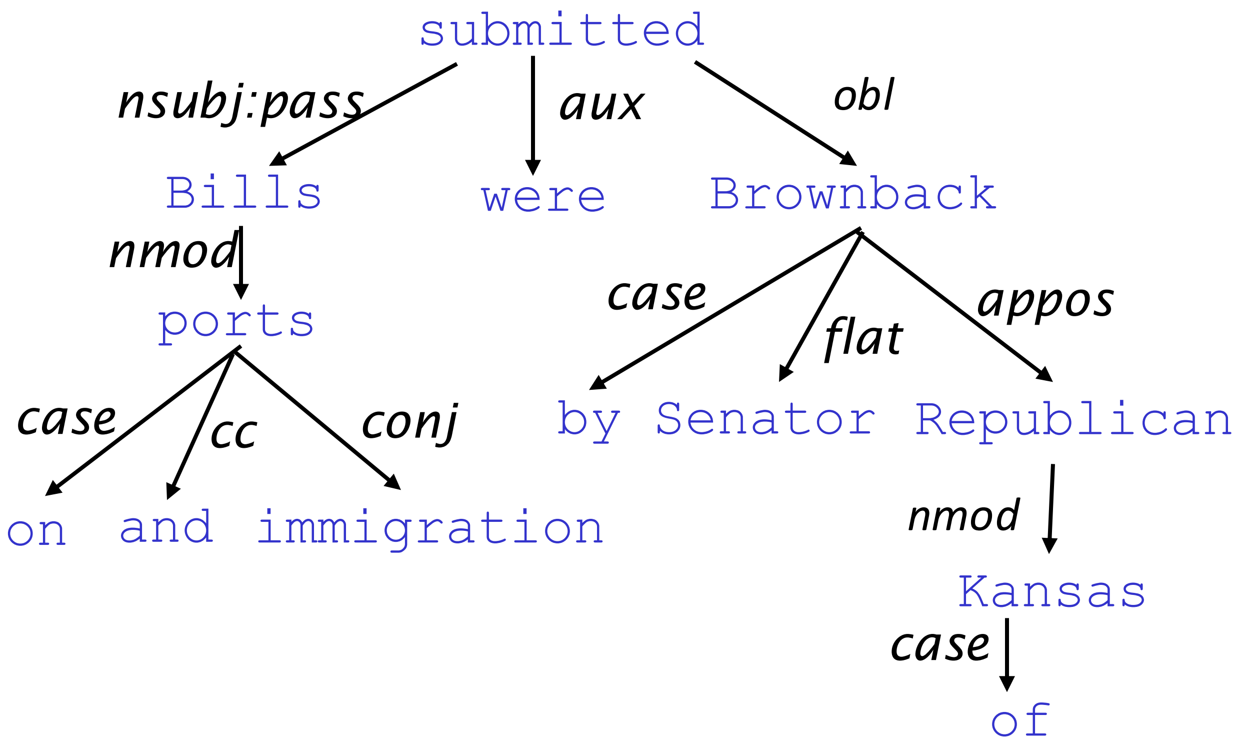


Dependency Grammar and Dependency Structure

Dependency syntax postulates that syntactic structure consists of relations between lexical items, normally binary asymmetric relations (“arrows”) called dependencies

An arrow connects a head with a dependent

Usually, dependencies form a tree (a connected, acyclic, single-root graph)



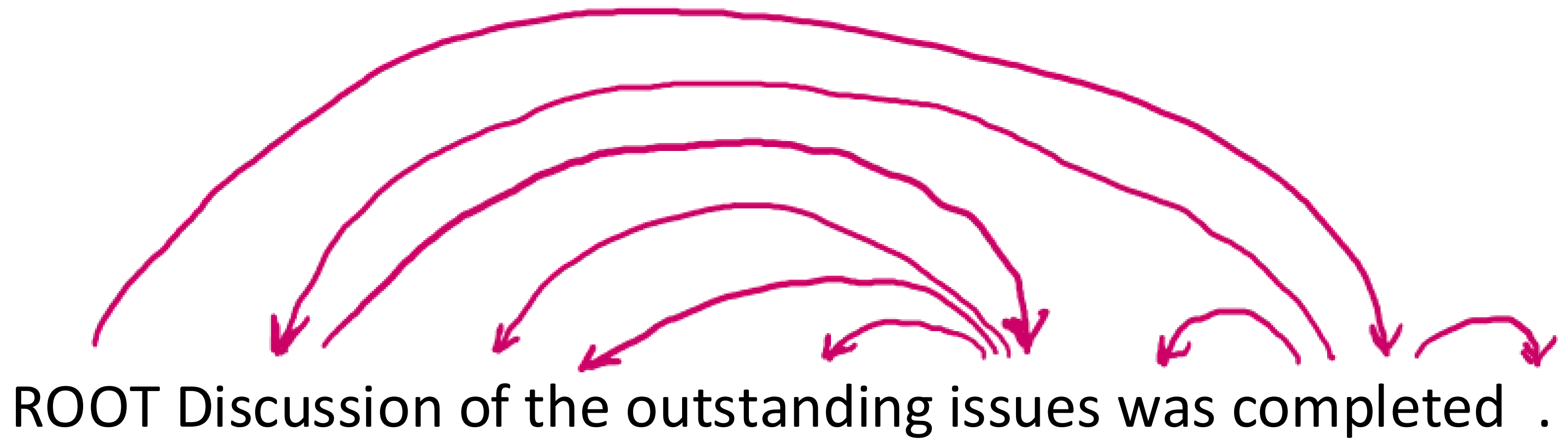
Pāṇini's grammar (c. 5th century BCE)

Gallery: http://wellcomeimages.org/indexplus/image/L0032691.html
CC BY 4.0 File:Birch bark MS from Kashmir of the Rupavatra Wellcome L0032691.jpg
But this comes from much later – originally the grammar was **oral**

Dependency Grammar/Parsing History

- The idea of dependency structure goes back a long way
  - To Pāṇini's grammar (c. 5th century BCE)
  - Basic approach of 1st millennium Arabic grammarians
- Constituency/context-free grammar is a new-fangled invention
  - 20th century invention (R.S. Wells, 1947; then Chomsky 1953, etc.)
- Modern dependency work is often sourced to Lucien Tesnière (1959)
  - Was dominant approach in "East" in 20th Century (Russia, China, …)
    - Good for free-er word order, inflected languages like Russian (or Latin!)
- Used in some of the earliest parsers in NLP, even in the US:
  - David Hays, one of the founders of U.S. computational linguistics, built early (first?) dependency parser (Hays 1962) and published on dependency grammar in *Language*

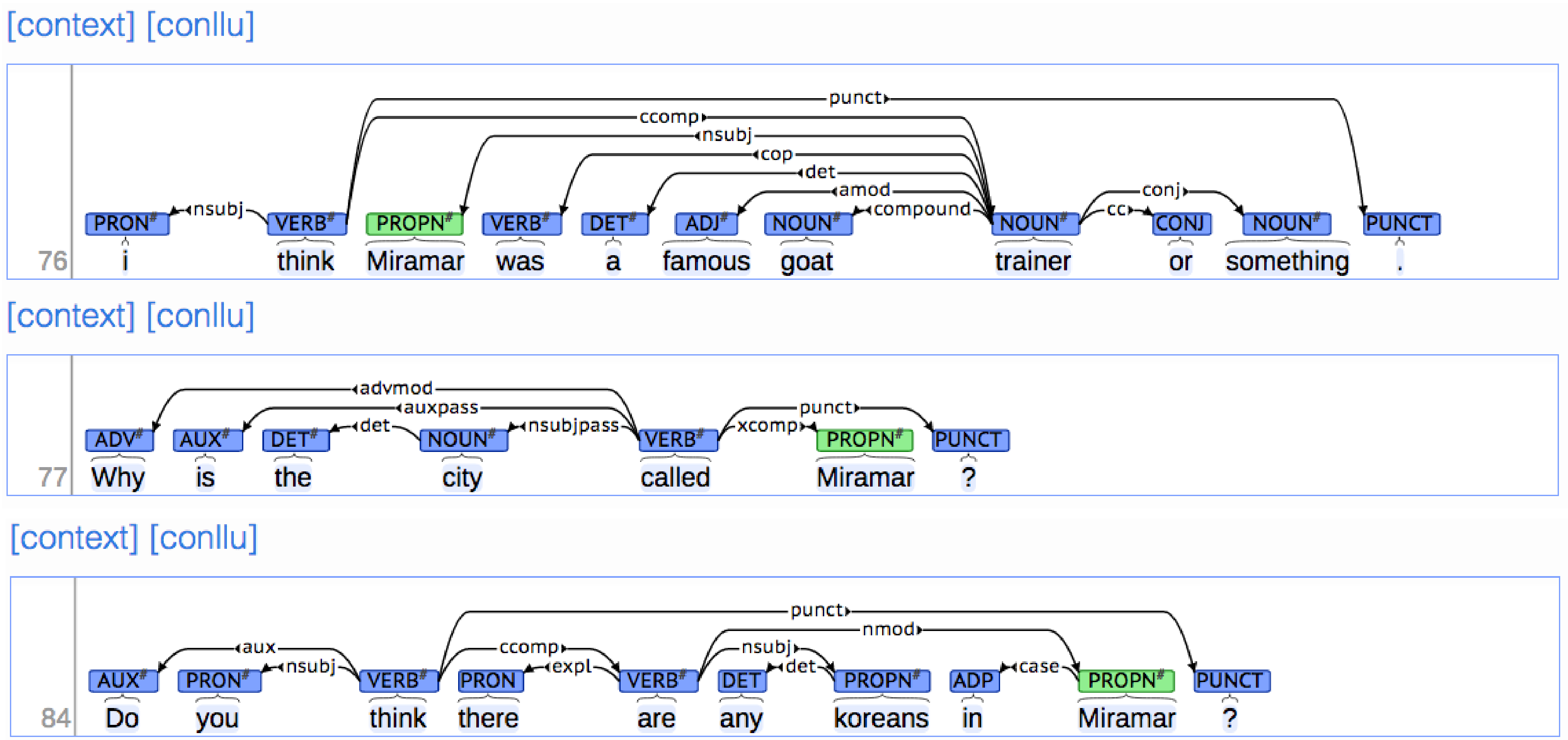
Dependency Grammar and Dependency Structure



- Some people draw the arrows one way; some the other way!
  - Tesnière had them point from head to dependent – we follow that convention
- We usually add a fake ROOT so every word is a dependent of precisely 1 other node

The rise of annotated data & Universal Dependencies treebanks

Brown corpus (1967; PoS tagged 1979); Lancaster-IBM Treebank (starting late 1980s);
Marcus et al. 1993, The Penn Treebank, *Computational Linguistics;*
Universal Dependencies: http://universaldependencies.org/


[context] [conllu]
76 i think Miramar was a famous goat trainer or something .
PRON VERB PROPN VERB DET ADJ NOUN NOUN CONJ NOUN PUNCT
nsubj punct ccomp nsubj cop det amod compound cc conj
[context] [conllu]
77 Why is the city called Miramar ?
ADV AUX DET NOUN VERB PROPN PUNCT
advmod auxpass det nsubjpass xcomp punct
[context] [conllu]
84 Do you think there are any koreans in Miramar ?
AUX PRON VERB PRON VERB DET PROPN ADP PROPN PUNCT
aux nsubj ccomp expl punct nsubj det nmod case

The rise of annotated data

Starting off, building a treebank seems a lot slower and less useful than writing a grammar (by hand)

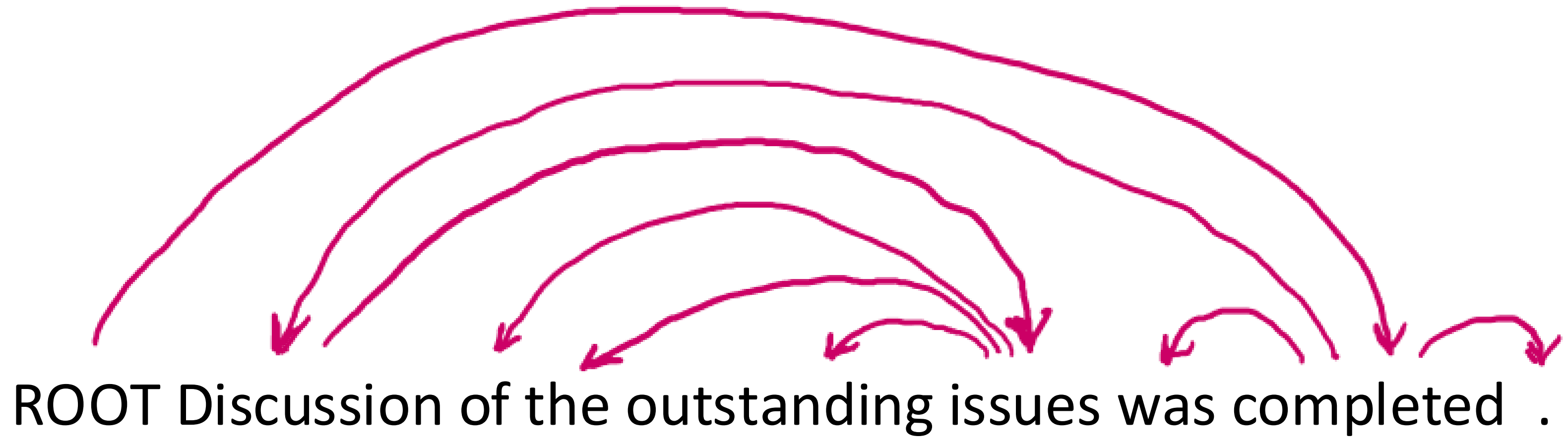
But a treebank gives us many things

- Reusability of the labor
  - Many parsers, part-of-speech taggers, etc. can be built on it
  - Valuable resource for linguistics
- Broad coverage, not just a few intuitions
- Frequencies and distributional information
- A way to evaluate NLP systems

Dependency Conditioning Preferences

What are the straightforward sources of information for dependency parsing?

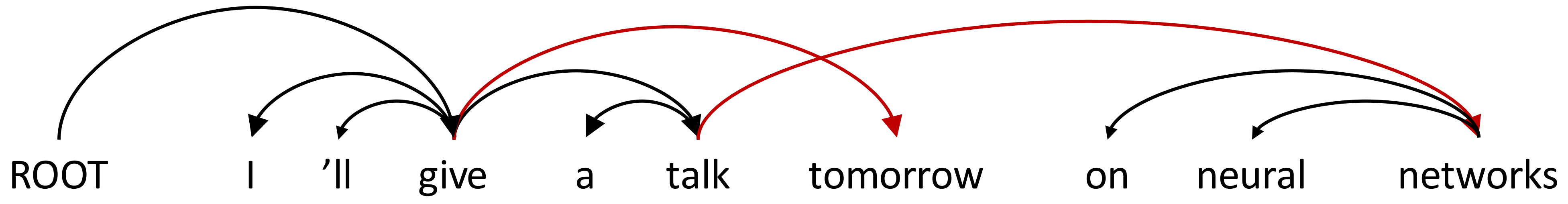
1. Bilexical affinities	The dependency [discussion → issues] is plausible
2. Dependency distance	Most dependencies are between nearby words
3. Intervening material	Dependencies rarely span intervening verbs or punctuation
4. Valency of heads	How many dependents on which side are usual for a head?



Dependency Parsing

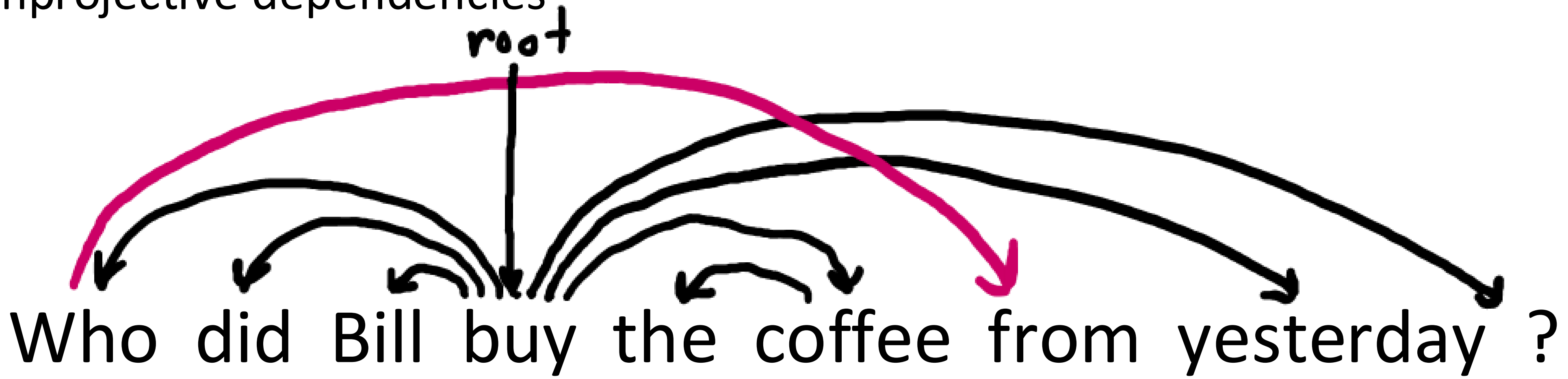
- A sentence is parsed by choosing for each word what other word (including ROOT) it is a dependent of

- Usually some constraints:
  - Only one word is a dependent of ROOT
  - Don’t want cycles A → B, B → A
- This makes the dependencies a tree
- Final issue is whether arrows can cross (be non-projective) or not



Projectivity

- Definition of a projective parse: There are no crossing dependency arcs when the words are laid out in their linear order, with all arcs above the words
- Dependencies corresponding to a CFG tree must be projective
  - I.e., by forming dependencies by taking 1 child of each category as head
- Most syntactic structure is projective like this, but dependency theory normally does allow non-projective structures to account for displaced constituents
  - You can't easily get the semantics of certain constructions right without these nonprojective dependencies



3. Methods of Dependency Parsing

1. Dynamic programming

   Eisner (1996) gives a clever algorithm with complexity O(n^3), by producing parse items with heads at the ends rather than in the middle

2. Graph algorithms

   You create a Minimum Spanning Tree for a sentence

   McDonald et al.’s (2005) O(n^2) MSTParser scores dependencies independently using an ML classifier (he uses MIRA, for online learning, but it can be something else)

   Neural graph-based parser: Dozat and Manning (2017) et seq. – very successful!

3. Constraint Satisfaction

   Edges are eliminated that don’t satisfy hard constraints. Karlsson (1990), etc.

4. “Transition-based parsing” or “deterministic dependency parsing”

   Greedy choice of attachments guided by good machine learning classifiers

   E.g., MaltParser (Nivre et al. 2008). Has proven highly effective. And fast.

Greedy transition-based parsing [Nivre 2003]

- A simple form of a greedy discriminative dependency parser
- The parser does a sequence of bottom-up actions
  - Roughly like “shift” or “reduce” in a shift-reduce parser – CS143, anyone?? – but the “reduce” actions are specialized to create dependencies with head on left or right
- The parser has:
  - a stack σ, written with top to the right
    - which starts with the ROOT symbol
  - a buffer β, written with top to the left
    - which starts with the input sentence
  - a set of dependency arcs A
    - which starts off empty
  - a set of actions

Basic transition-based dependency parser

Start: $\sigma = [\text{ROOT}]$, $\beta = w_1, \ldots, w_n$, $A = \emptyset$

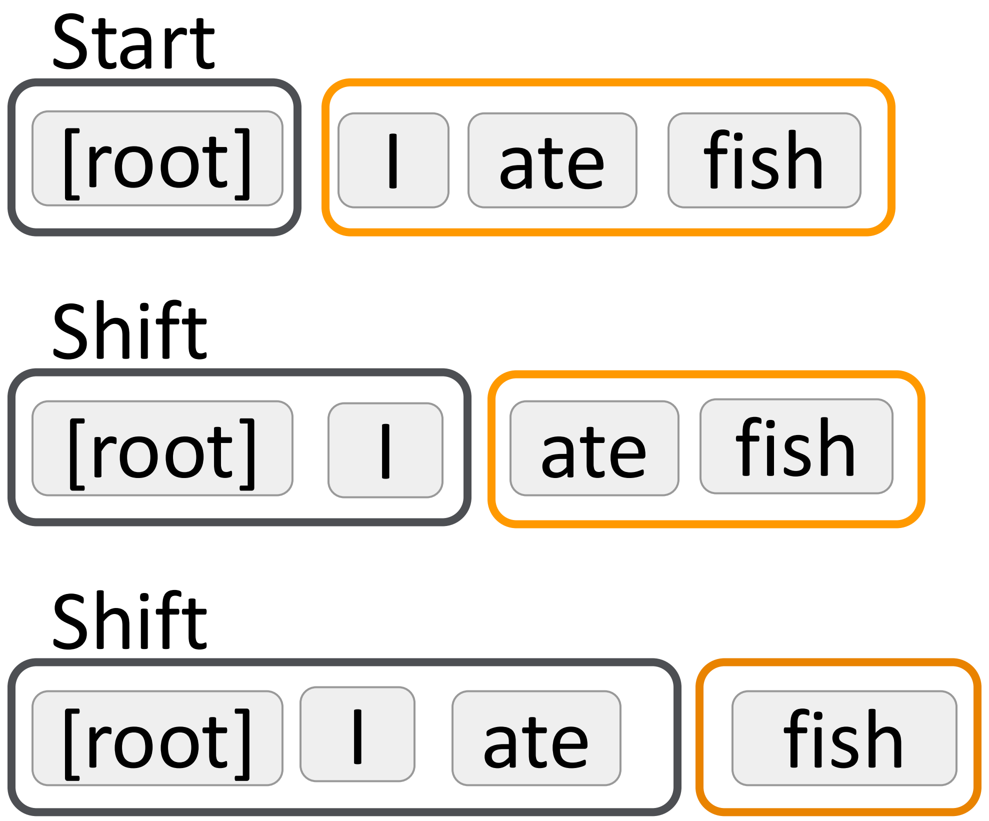
1. Shift $\quad \sigma, w_i|\beta, A \rightarrow \sigma|w_i, \beta, A$
2. Left-Arc$_r$ $\quad \sigma|w_i|w_j, \beta, A \rightarrow \sigma|w_j, \beta, A \cup \{r(w_j,w_i)\}$
3. Right-Arc$_r$ $\quad \sigma|w_i|w_j, \beta, A \rightarrow \sigma|w_i, \beta, A \cup \{r(w_i,w_j)\}$

Finish: $\sigma = [w]$, $\beta = \emptyset$

Arc-standard transition-based parser

(there are other transition schemes …)

Analysis of "I ate fish"



Start: $\sigma = [\text{ROOT}]$, $\beta = w_1, \ldots, w_n$, $A = \emptyset$

1. Shift $\sigma, w_i|\beta, A \rightarrow \sigma|w_i, \beta, A$
2. Left-Arc$_r$ $\sigma|w_i|w_j, \beta, A \rightarrow$ $\sigma|w_j, \beta, A \cup \{r(w_j,w_i)\}$
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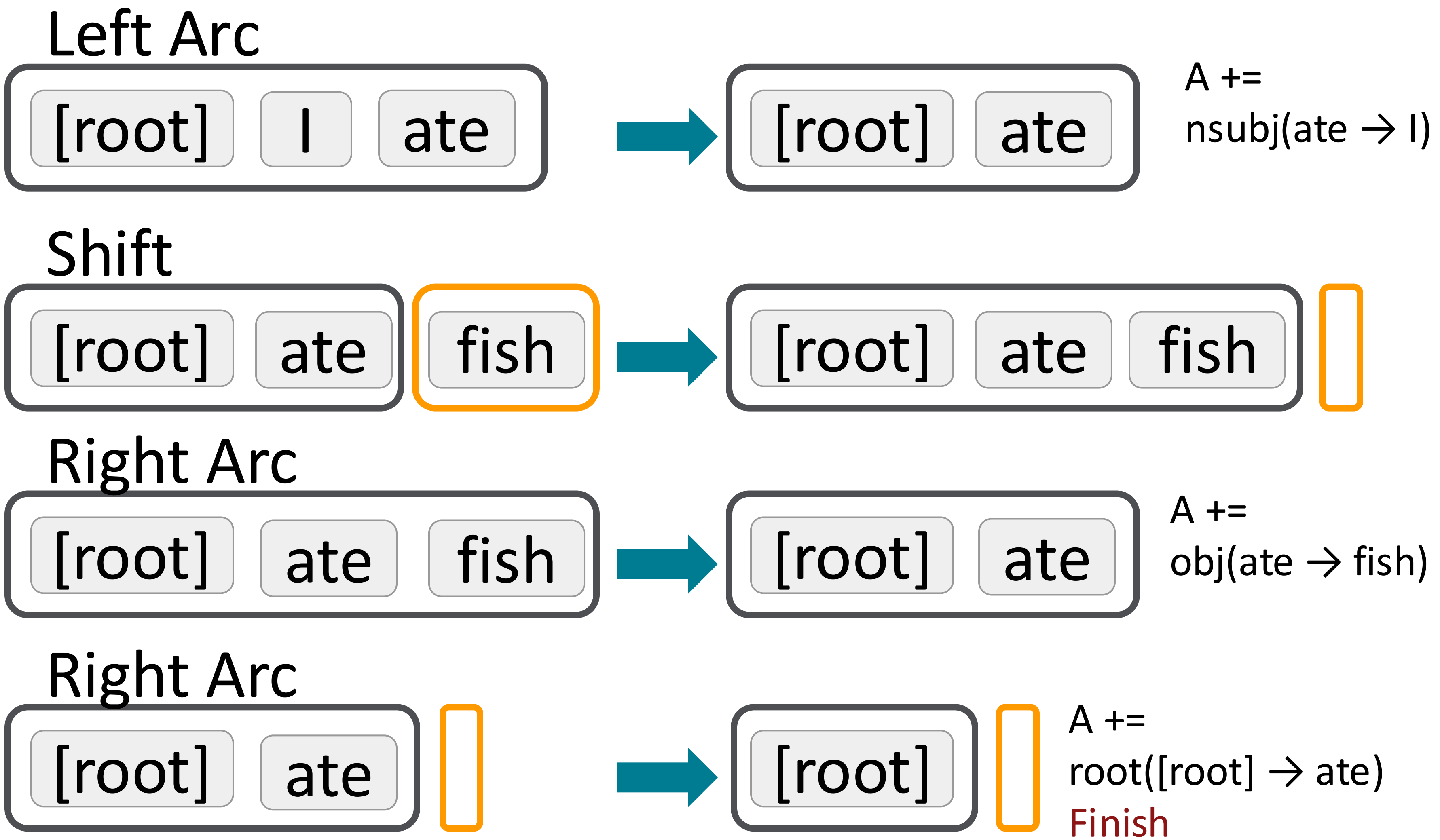


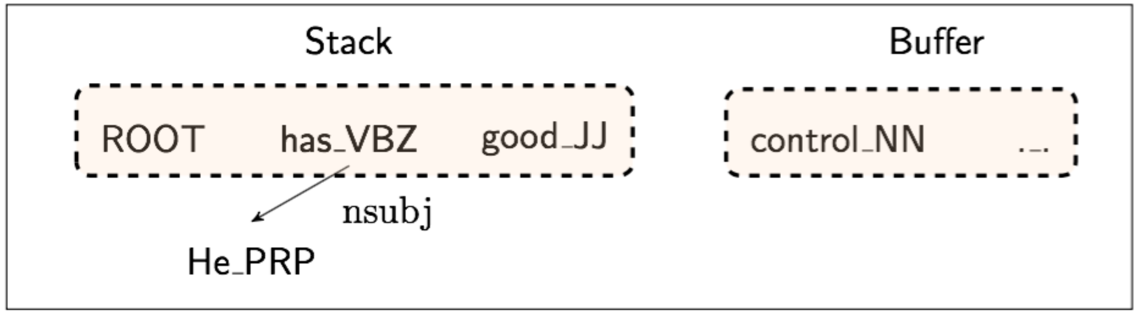
Nota bene: In this example I’ve at each step made the “correct” next transition. But a parser has to work this out – by exploring or inferring!

A = { nsubj(ate → I), obj(ate → fish) root([root] → ate) }

MaltParser [Nivre and Hall 2005]

- We have left to explain how we choose the next action 🤷‍♀️
  - Answer: Stand back, I know machine learning!
- Each action is predicted by a discriminative classifier (e.g., softmax classifier) over each legal move
  - Max of 3 untyped choices (max of $|R| \times 2 + 1$ when typed)
  - Features: top of stack word, POS; first in buffer word, POS; etc.
- There is NO search (in the simplest form)
  - But you can profitably do a beam search if you wish (slower but better):
    - You keep *k* good parse prefixes at each time step
- The model's accuracy is *fractionally* below the state of the art in dependency parsing, but
- It provides **very fast linear time parsing**, with high accuracy – great for parsing the web

Conventional Feature Representation



binary, sparse
dim $=10^6 – 10^7$

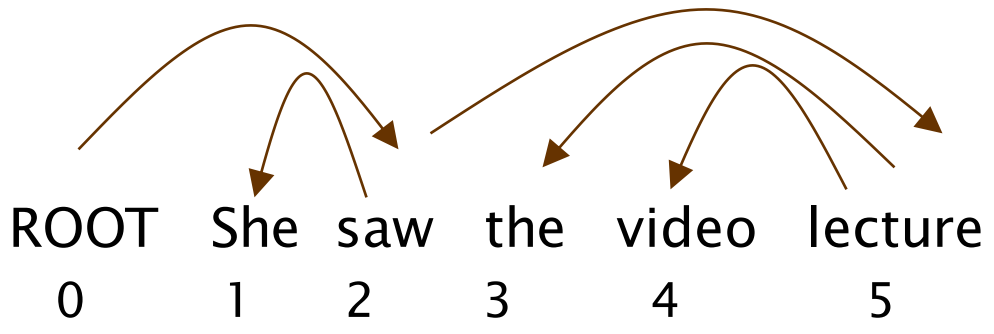
0	0	0	1	0	0	1	0	…	0	0	1	0

Feature templates: usually a combination of 1–3 elements from the configuration

Indicator features

$$s1.w = \text{good} \wedge s1.t = \text{JJ}$$
$$s2.w = \text{has} \wedge s2.t = \text{VBZ} \wedge s1.w = \text{good}$$
$$lc(s_2).t = \text{PRP} \wedge s_2.t = \text{VBZ} \wedge s_1.t = \text{JJ}$$
$$lc(s_2).w = \text{He} \wedge lc(s_2).l = \text{nsubj} \wedge s_2.w = \text{has}$$

Evaluation of Dependency Parsing: (labeled) dependency accuracy



$$\text{Acc} = \frac{\text{\# correct deps}}{\text{\# of deps}}$$

UAS = 4 / 5 = 80%

LAS = 2 / 5 = 40%

Gold			
1	2	She	nsubj
2	0	saw	root
3	5	the	det
4	5	video	nn
5	2	lecture	obj

Parsed			
1	2	She	nsubj
2	0	saw	root
3	4	the	det
4	5	video	nsubj
5	2	lecture	ccomp

4. Why do we gain from a neural dependency parser? Indicator Features Revisited

Categorical features are:

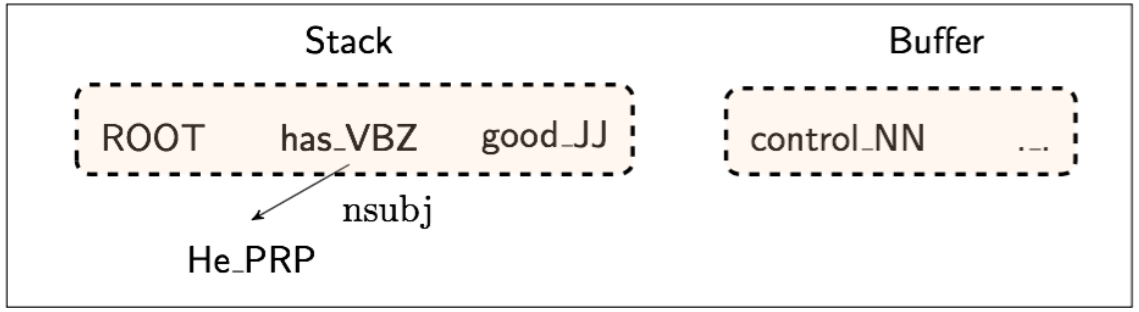
- Problem #1: sparse
- Problem #2: incomplete
- Problem #3: expensive to compute

More than 95% of parsing time is consumed by feature computation

$$s1.w = \text{good} \wedge s1.t = \text{JJ}$$
$$s2.w = \text{has} \wedge s2.t = \text{VBZ} \wedge s1.w = \text{good}$$
$$lc(s_2).t = \text{PRP} \wedge s_2.t = \text{VBZ} \wedge s_1.t = \text{JJ}$$
$$lc(s_2).w = \text{He} \wedge lc(s_2).l = \text{nsubj} \wedge s_2.w = \text{has}$$

Neural Approach:

learn a dense and compact feature representation



dense
dim = ~1000

0.1	0.9	-0.2	0.3	...	-0.1	-0.5

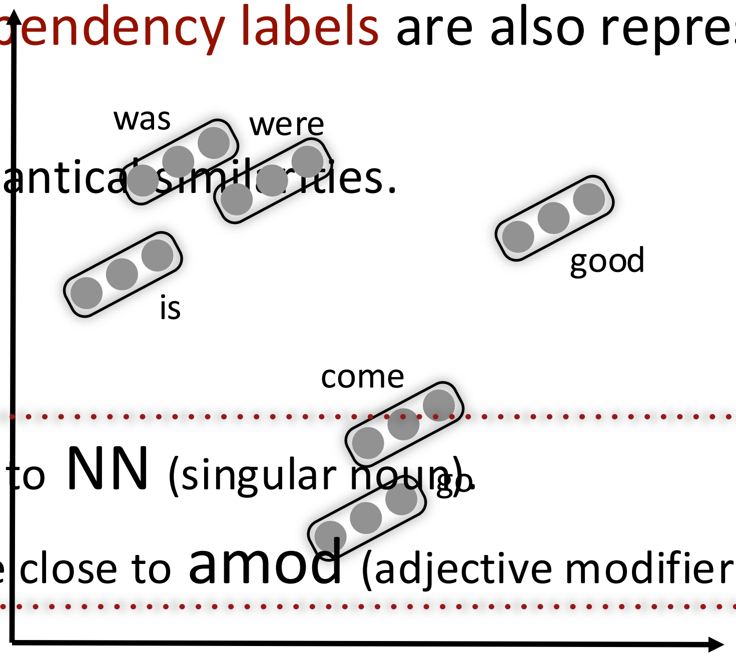
A neural dependency parser [Chen and Manning 2014]

- Results on English parsing to Stanford Dependencies:
  - Unlabeled attachment score (UAS) = head
  - Labeled attachment score (LAS) = head and label

Parser	UAS	LAS	sent. / s
MaltParser	89.8	87.2	469
MSTParser	91.4	88.1	10
TurboParser	**92.3**	89.6	8
C & M 2014	92.0	**89.7**	**654**

First win: Distributed Representations

- We represent each word as a *d*-dimensional dense vector (i.e., word embedding)
  - Similar words are expected to have close vectors.
- Meanwhile, part-of-speech tags (POS) and dependency labels are also represented as *d*-dimensional vectors.
  - The smaller discrete sets also exhibit many semantical similarities.

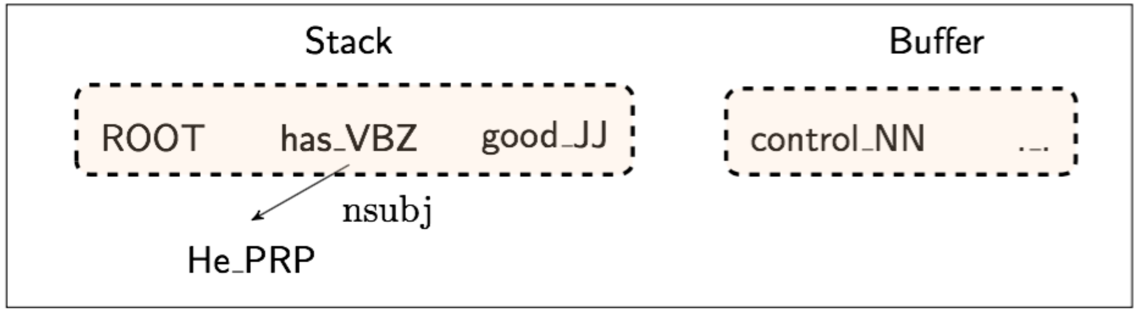


NNS (plural noun) should be close to NN (singular noun).

nummod (numerical modifier) should be close to amod (adjective modifier).

Extracting Tokens & vector representations from configuration

- We extract a set of tokens based on the stack / buffer positions:



	word		POS		dep.
s1	good		JJ		∅
s2	has		VBZ		∅
b1	control		NN		∅
lc(s1)	∅	+	∅	+	∅
rc(s1)	∅		∅		∅
lc(s2)	He		PRP		nsubj
rc(s2)	∅		∅		∅

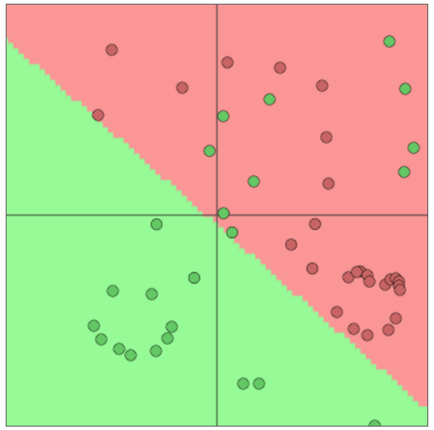
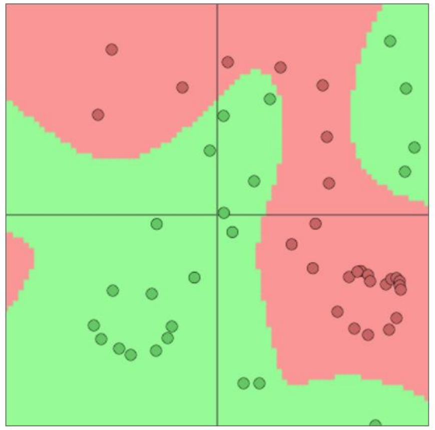
A concatenation of the vector representation of all these is the neural representation of a configuration

Second win: Deep Learning classifiers are non-linear classifiers

- A softmax classifier assigns classes $y \in C$ based on inputs $x \in \mathbb{R}^d$ via the probability:

$$p(y|x) = \frac{\exp(W_y.x)}{\sum_{c=1}^{C} \exp(W_c.x)}$$

- Traditional ML classifiers (including Naïve Bayes, SVMs, logistic regression and softmax classifier) are not very powerful classifiers: they only give linear decision boundaries
- But neural networks can use multiple layers to learn much more complex nonlinear decision boundaries

Neural Dependency Parser Model Architecture
(A simple feed-forward neural network multi-class classifier)

Log loss (cross-entropy error) will be back-propagated to the embeddings

Softmax probabilities $\longrightarrow$ { Shift , Left-Arc$_r$, Right-Arc$_r$ }

Output layer y

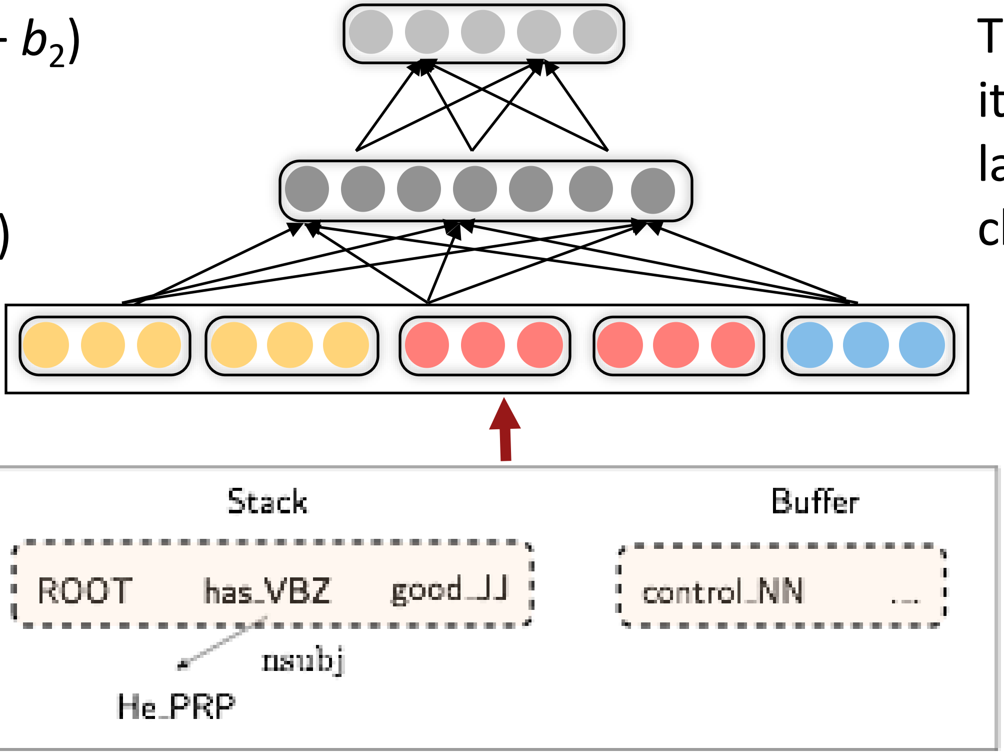
$y = \text{softmax}(Uh + b_2)$

Hidden layer h

$h = \text{ReLU}(Wx + b_1)$

Input layer x

lookup + concat

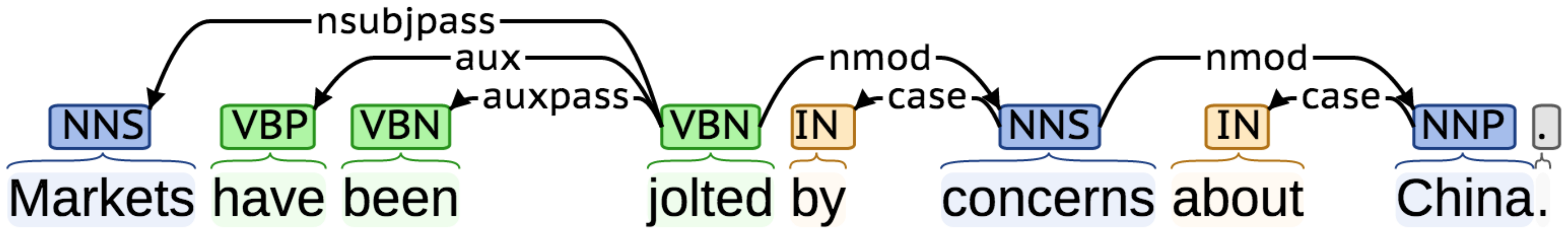


The hidden layer re-represents the input — it moves inputs around in an intermediate layer vector space—so it can be easily classified with a (linear) softmax

Wins:
Distributed representations!
Non-linear classifier!

Dependency parsing for sentence structure

Chen & Manning (2014) showed that neural networks can accurately determine the structure of sentences, supporting meaning interpretation



This paper was the first simple and successful neural dependency parser

The dense representations (and non-linear classifier) let it outperform other greedy parsers in both accuracy and speed

Further developments in transition-based neural dependency parsing

This work was further developed and improved by others, including in particular at Google

- Bigger, deeper networks with better tuned hyperparameters
- Beam search
- Global, conditional random field (CRF)-style inference over the decision sequence

Leading to SyntaxNet and the Parsey McParseFace model (2016):

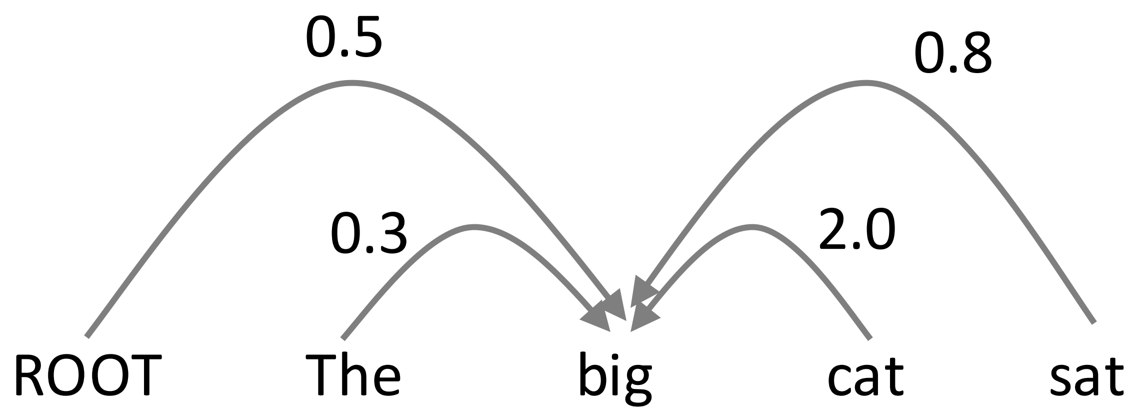
"The World's Most Accurate Parser"

https://research.googleblog.com/2016/05/announcing-syntaxnet-worlds-most.html

Method	UAS	LAS (PTB WSJ SD 3.3)
Chen & Manning 2014	92.0	89.7
Weiss et al. 2015	93.99	92.05
Andor et al. 2016	94.61	92.79

Graph-based dependency parsers

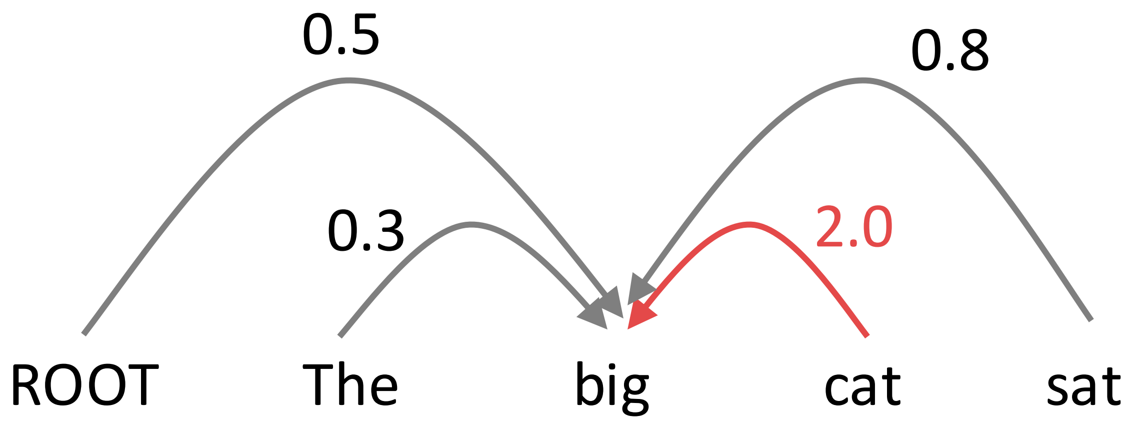
- Compute a score for every possible dependency for each word
  - Doing this well requires good “contextual” representations of each word token, which we will develop in coming lectures



e.g., picking the head for “big”

Graph-based dependency parsers

- Compute a score for every possible dependency (choice of head) for each word
  - Doing this well requires more than just knowing the two words
  - We need **good "contextual" representations** of each word token, which we will develop in the coming lectures
- Repeat the same process for each other word; find the best parse (MST algorithm)



e.g., picking the head for "big"

A Neural graph-based dependency parser

[Dozat and Manning 2017; Dozat, Qi, and Manning 2017]

- This paper revived interest in graph-based dependency parsing in a neural world
  - Designed a biaffine scoring model for neural dependency parsing
    - Also crucially uses a neural sequence model, something we discuss later
- Really great results!
  - **But slower than the simple neural transition-based parsers**
    - There are n^2 possible dependencies in a sentence of length n

Method	UAS	LAS (PTB WSJ SD 3.3)
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Dozat & Manning 2017	**95.74**	**94.08**