Natural Language Processing with Deep Learning

CS224N/Ling284

Richard Socher

Lecture 14: Tree Recursive Neural Networks and Constituency Parsing

Lecture Plan

1. Motivation: Compositionality and Recursion
2. Structure prediction with simple Tree RNN: Parsing
3. Backpropagation through Structure
4. More complex units

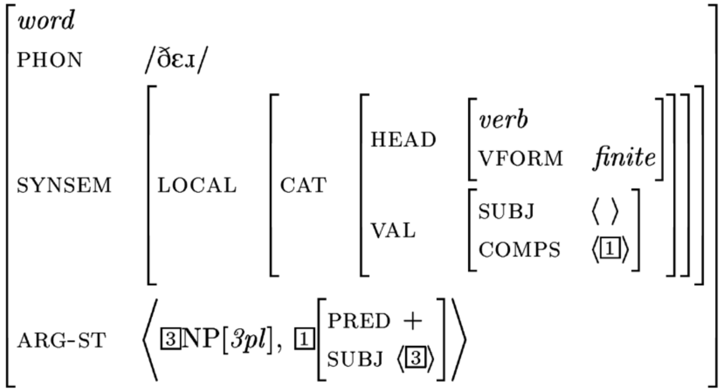
Reminders/comments:

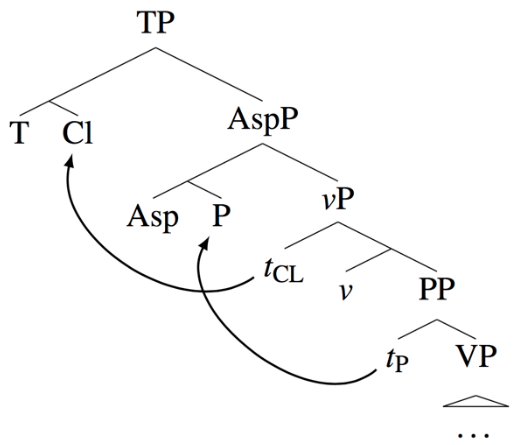
Learn up on GPUs, Azure, Docker

Ass 4: Get something working, using a GPU for milestone

Final project discussions – come meet with us!
OH today after class. You have to come to every OH. No additional feedback beyond OH. Nothing on gradescope.

1. The spectrum of language in CS





Semantic interpretation of language – Not just word vectors

How can we know when larger units are similar in meaning?

- *The **snowboarder** is leaping over a mogul*
- *A **person on a snowboard** jumps into the air*

People interpret the meaning of larger text units – entities, descriptive terms, facts, arguments, stories – by **semantic composition** of smaller elements

Compositionality

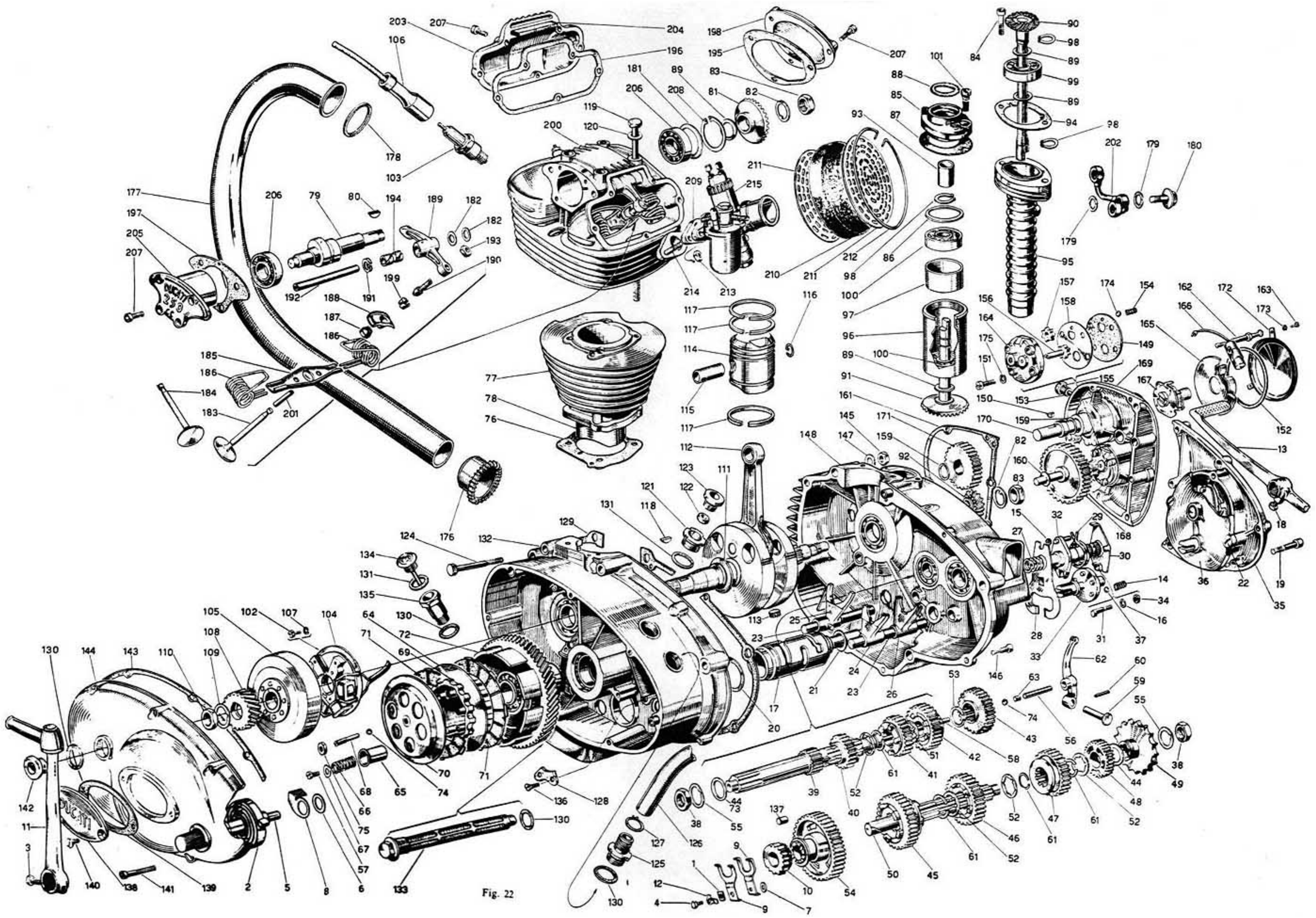
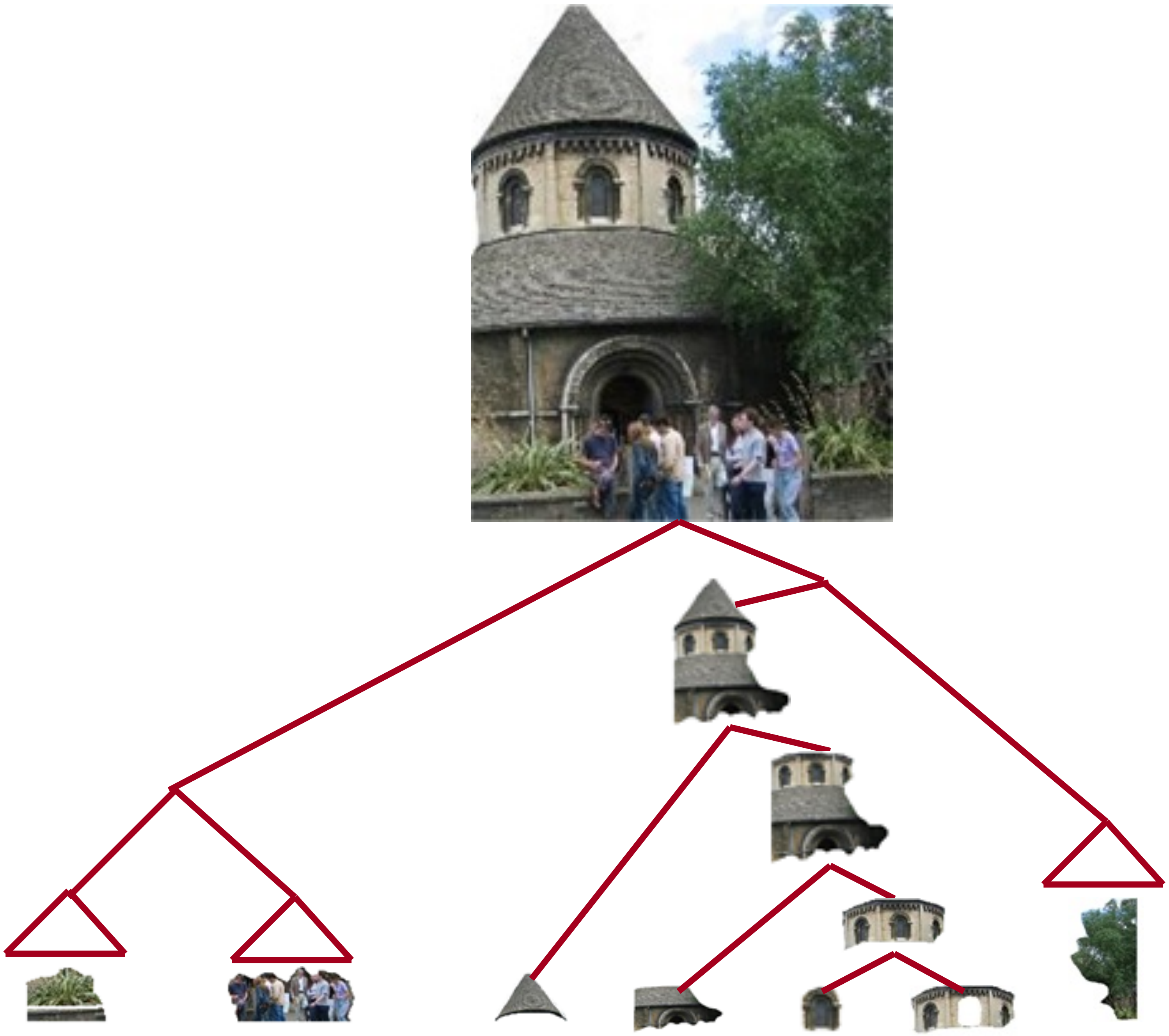


Fig. 22



Language understanding – & Artificial Intelligence – requires being able to understand bigger things from knowing about smaller parts

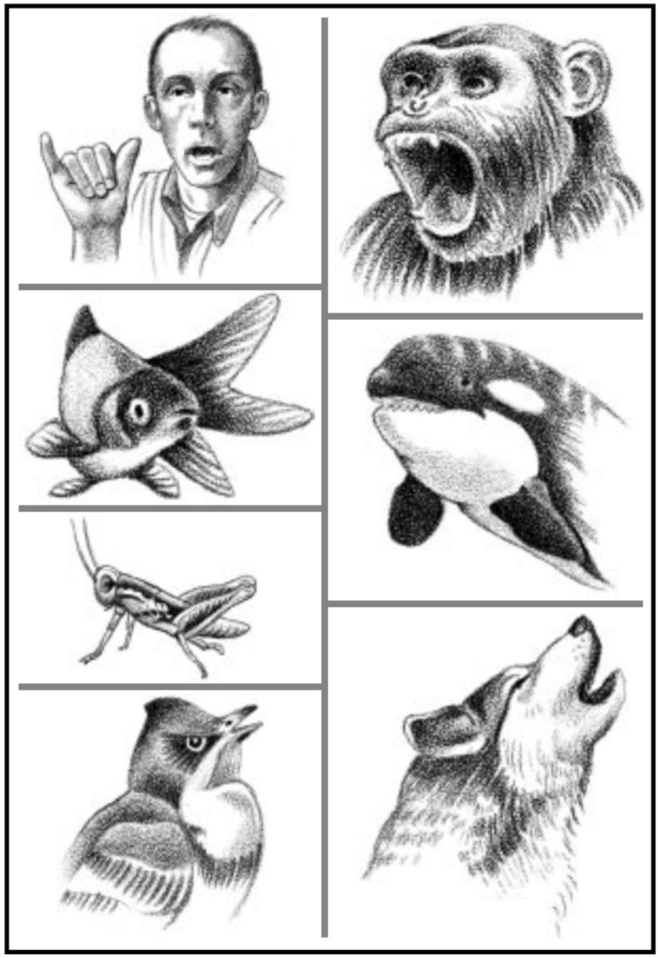
REVIEW: NEUROSCIENCE

The Faculty of Language: What Is It, Who Has It, and How Did It Evolve?

Marc D. Hauser,[1*] Noam Chomsky,[2] W. Tecumseh Fitch[1]

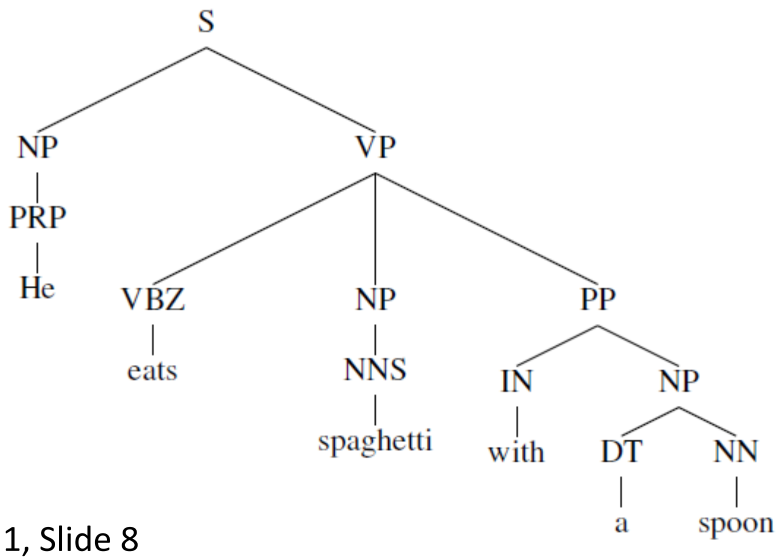
We argue that an understanding of the faculty of language requires substantial interdisciplinary cooperation. We suggest how current developments in linguistics can be profitably wedded to work in evolutionary biology, anthropology, psychology, and neuroscience. We submit that a distinction should be made between the faculty of language in the broad sense (FLB) and in the narrow sense (FLN). FLB includes a sensory-motor system, a conceptual-intentional system, and the computational mechanisms for recursion, providing the capacity to generate an infinite range of expressions from a finite set of elements. We hypothesize that FLN only includes recursion and is the only uniquely human component of the faculty of language. We further argue that FLN may have evolved for reasons other than language, hence comparative studies might look for evidence of such computations outside of the domain of communication (for example, number, navigation, and social relations).

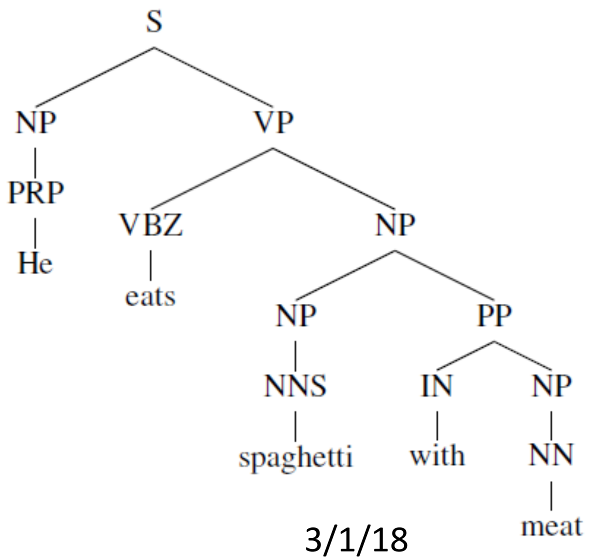
If a martian graced our planet, it would be struck by one remarkable similarity among Earth's living creatures and a key difference. Concerning similarity, it would note that all



Are languages recursive?

- Cognitively somewhat debatable
- But: recursion is natural for describing language
- *[The man from [the company that you spoke with about [the project] yesterday]]*
- noun phrase containing a noun phrase containing a noun phrase
- Arguments for now: 1) Helpful in disambiguation:





Is recursion useful?

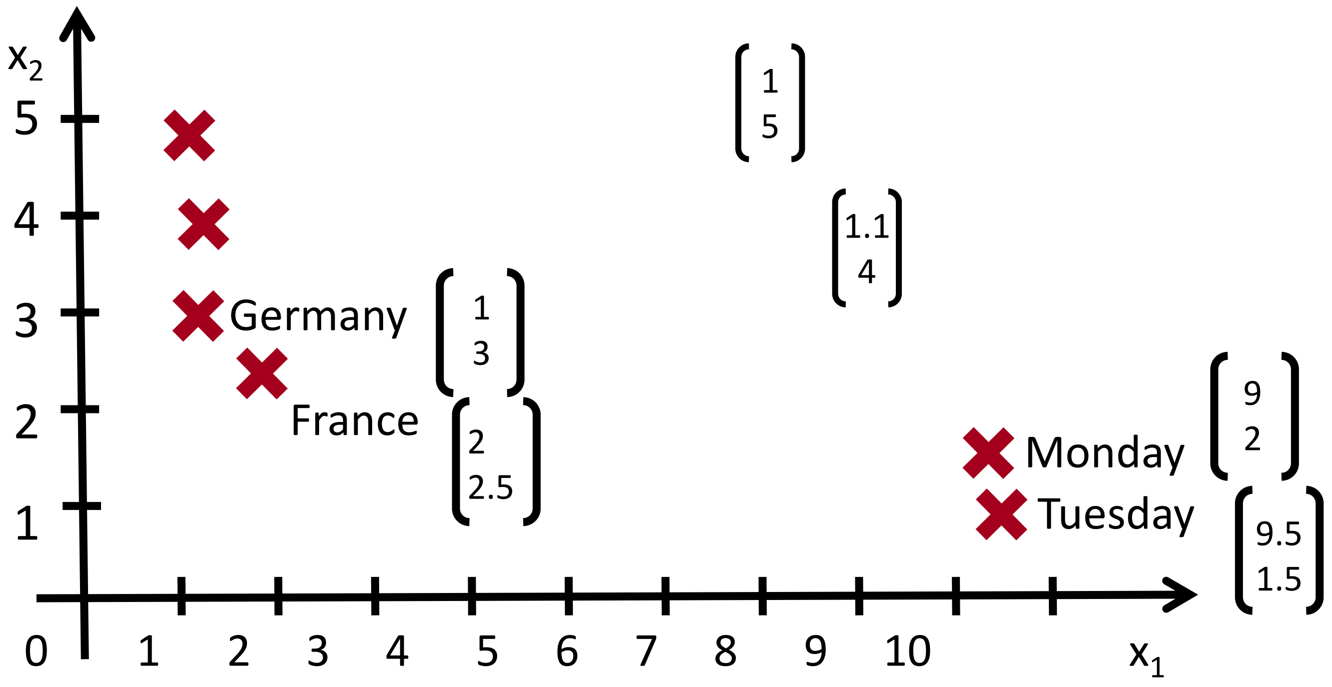
2) Helpful for some tasks to refer to specific phrases:

- John and Jane went to a big festival. They enjoyed the trip and the music there.
- “they”: John and Jane
- “the trip”: went to a big festival
- “there”: big festival

3) Works better for some tasks to use grammatical tree structure

- It’s a powerful prior for language structure

Building on Word Vector Space Models



the country of my birth

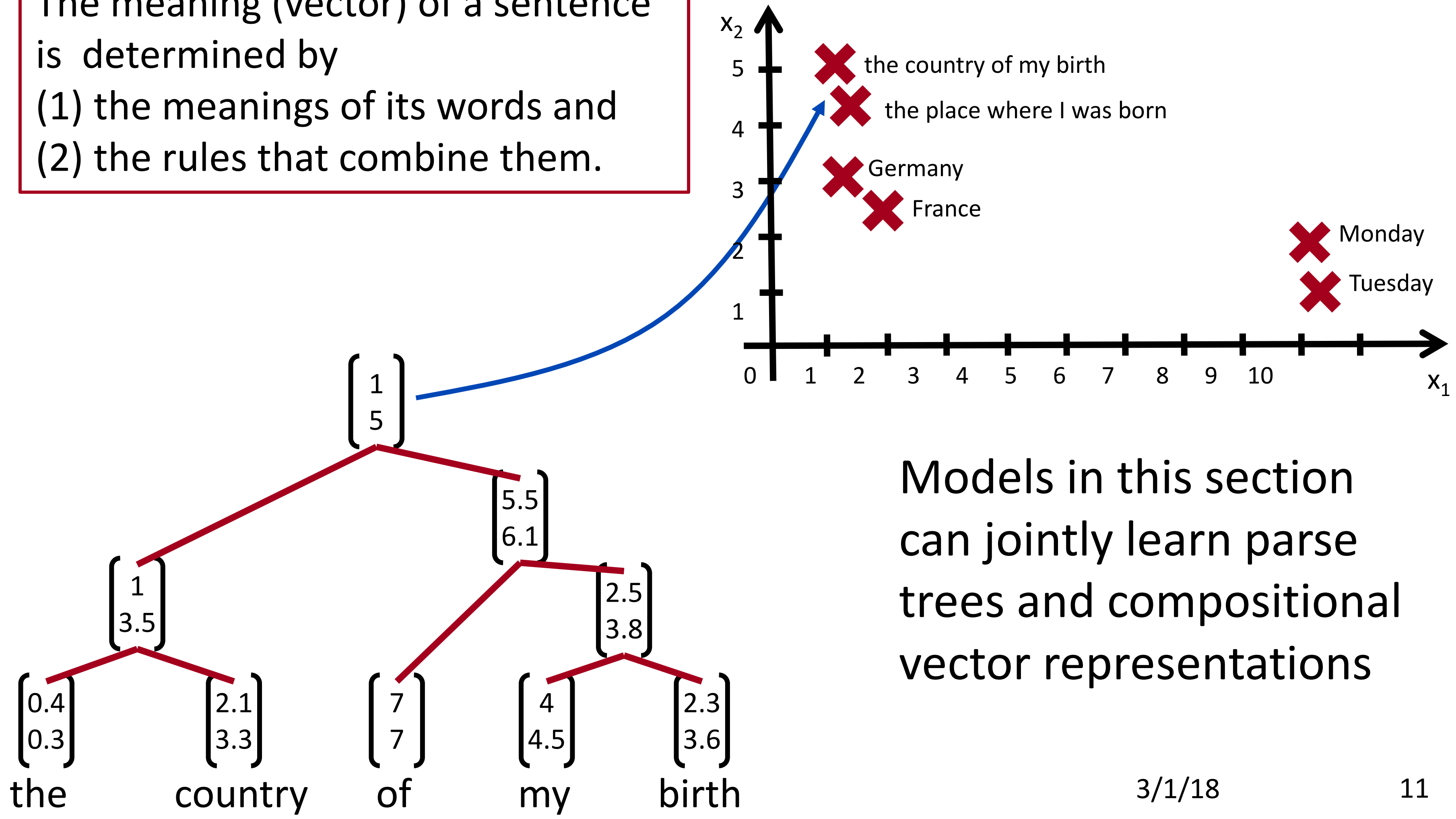
the place where I was born

How can we represent the meaning of longer phrases?

By mapping them into the same vector space!

How should we map phrases into a vector space?

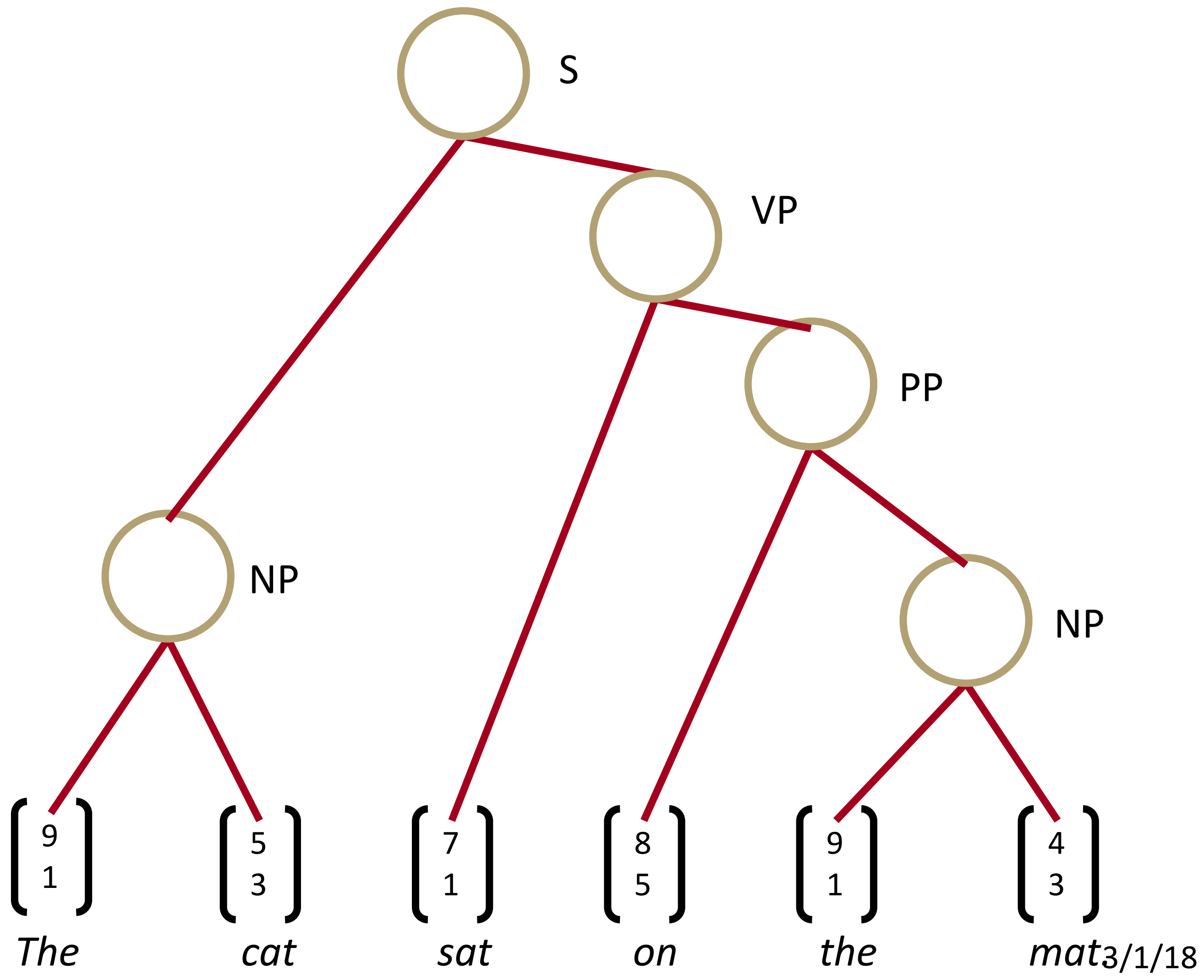
Use principle of compositionality
The meaning (vector) of a sentence is determined by (1) the meanings of its words and (2) the rules that combine them.



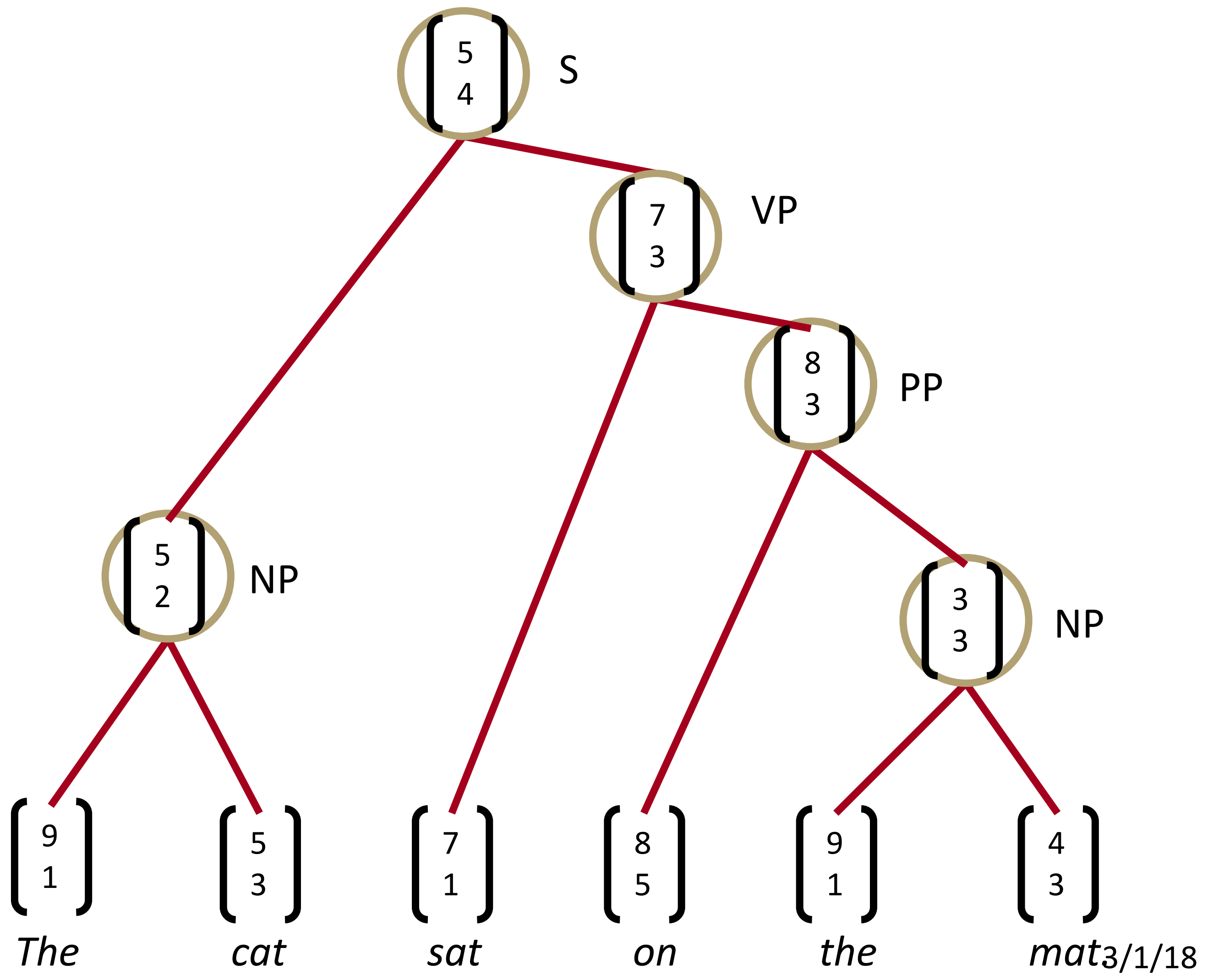
x_2
x_1
0
1
2
3
4
5
6
7
8
9
10
the country of my birth
the place where I was born
Germany
France
Monday
Tuesday
$\begin{bmatrix}1\\5\end{bmatrix}$
$\begin{bmatrix}1\\3.5\end{bmatrix}$
$\begin{bmatrix}5.5\\6.1\end{bmatrix}$
$\begin{bmatrix}2.5\\3.8\end{bmatrix}$
$\begin{bmatrix}0.4\\0.3\end{bmatrix}$
$\begin{bmatrix}2.1\\3.3\end{bmatrix}$
$\begin{bmatrix}7\\7\end{bmatrix}$
$\begin{bmatrix}4\\4.5\end{bmatrix}$
$\begin{bmatrix}2.3\\3.6\end{bmatrix}$
the
country
of
my
birth

Models in this section can jointly learn parse trees and compositional vector representations

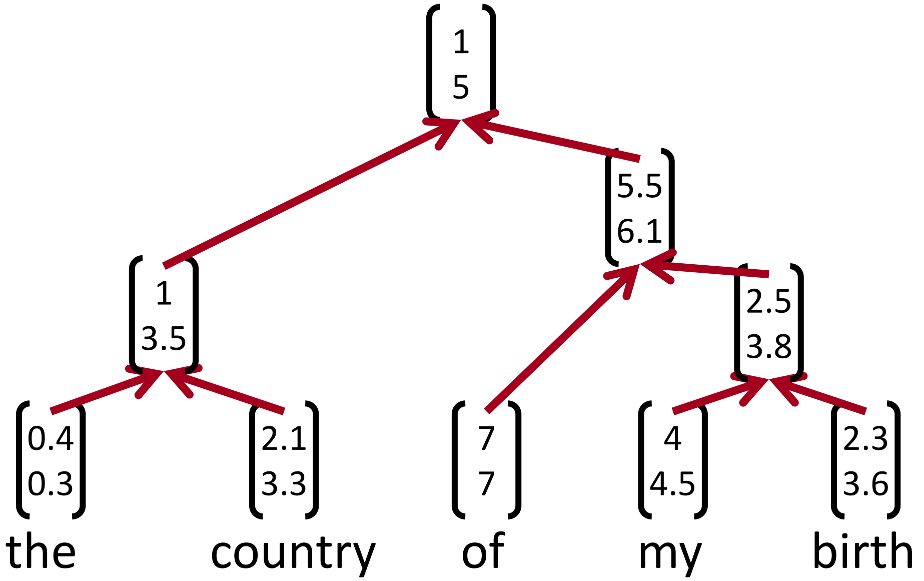
Constituency Sentence Parsing: What we want

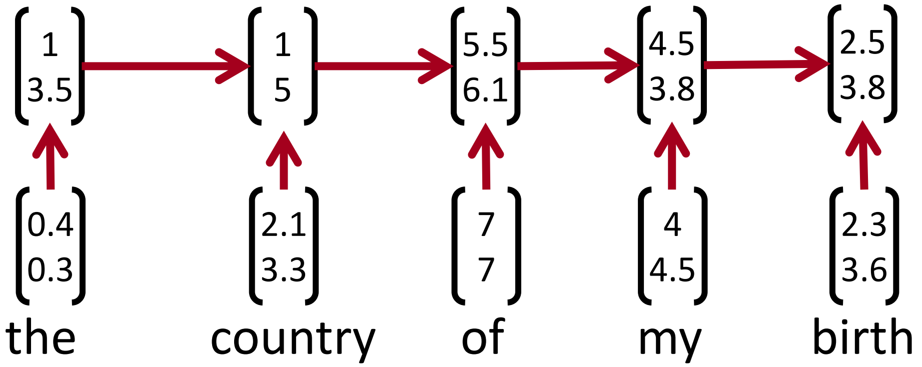


Learn Structure and Representation



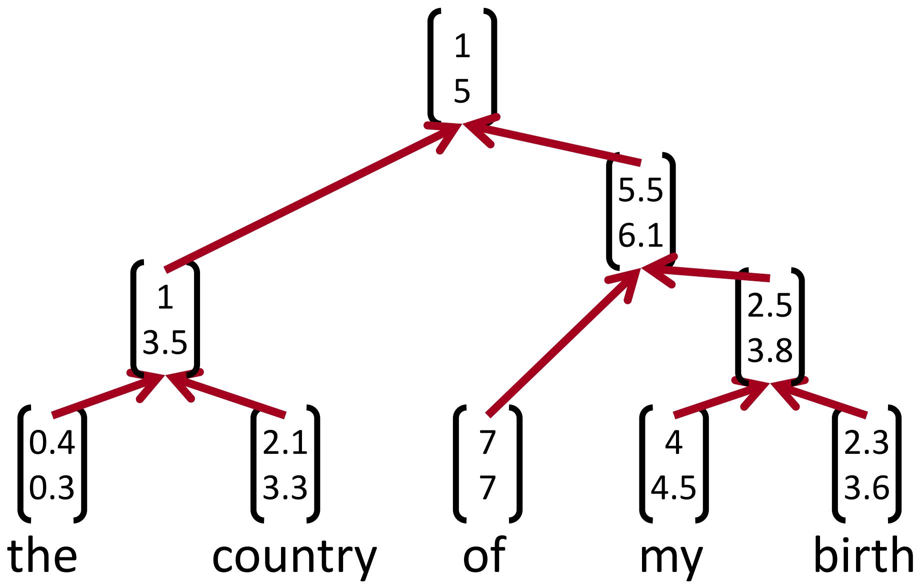
Recursive vs. recurrent neural networks



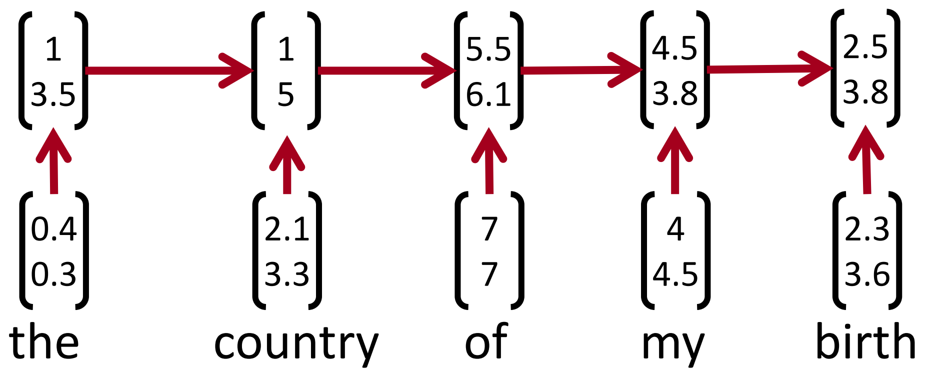


Recursive vs. recurrent neural networks

- Recursive neural nets require a tree structure



- Recurrent neural nets cannot capture phrases without prefix context and often capture too much of last words in final vector

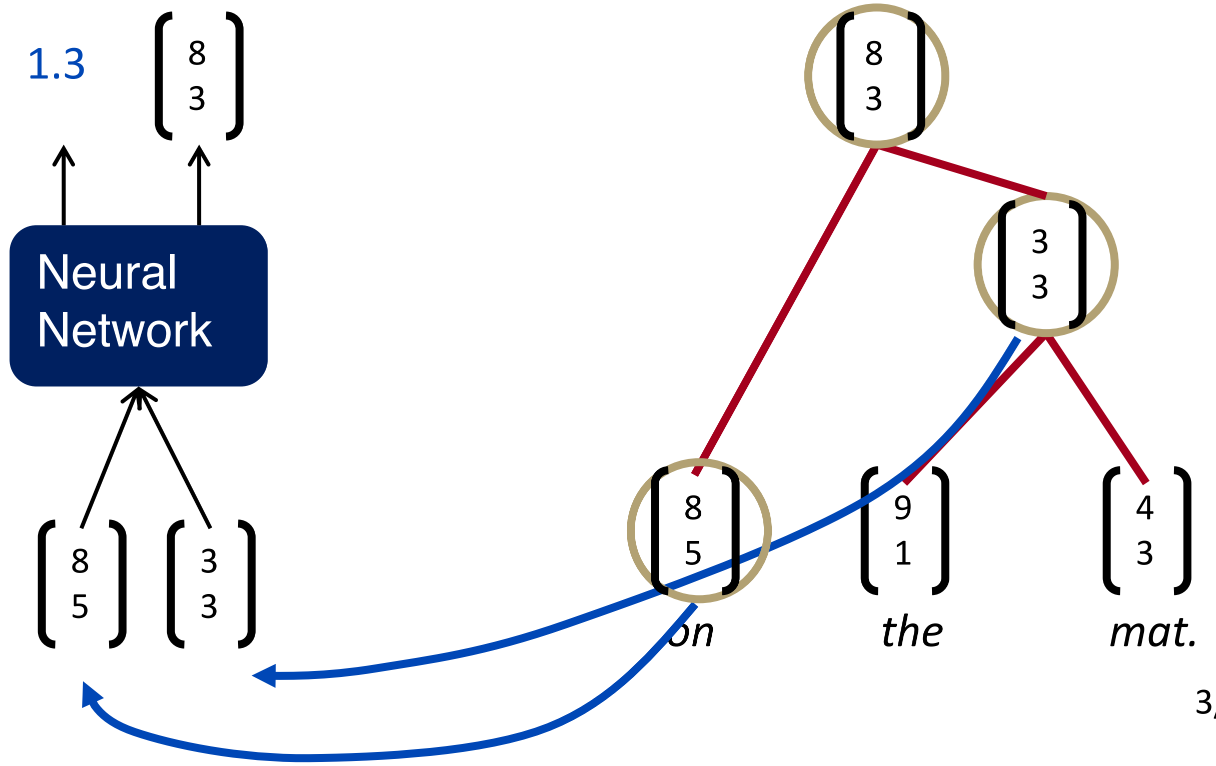


Recursive Neural Networks for Structure Prediction

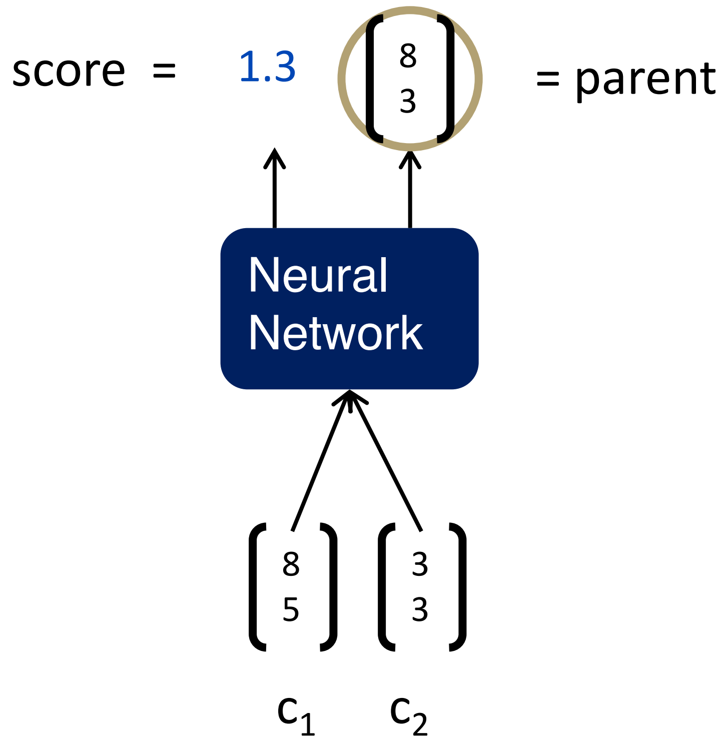
Inputs: two candidate children's representations

Outputs:

1. The semantic representation if the two nodes are merged.
2. Score of how plausible the new node would be.



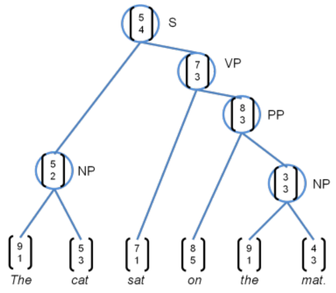
Recursive Neural Network Definition


score = 1.3
$\begin{bmatrix}8\\3\end{bmatrix}$ = parent
Neural Network
$\begin{bmatrix}8\\5\end{bmatrix}$ $\begin{bmatrix}3\\3\end{bmatrix}$
c_1 c_2

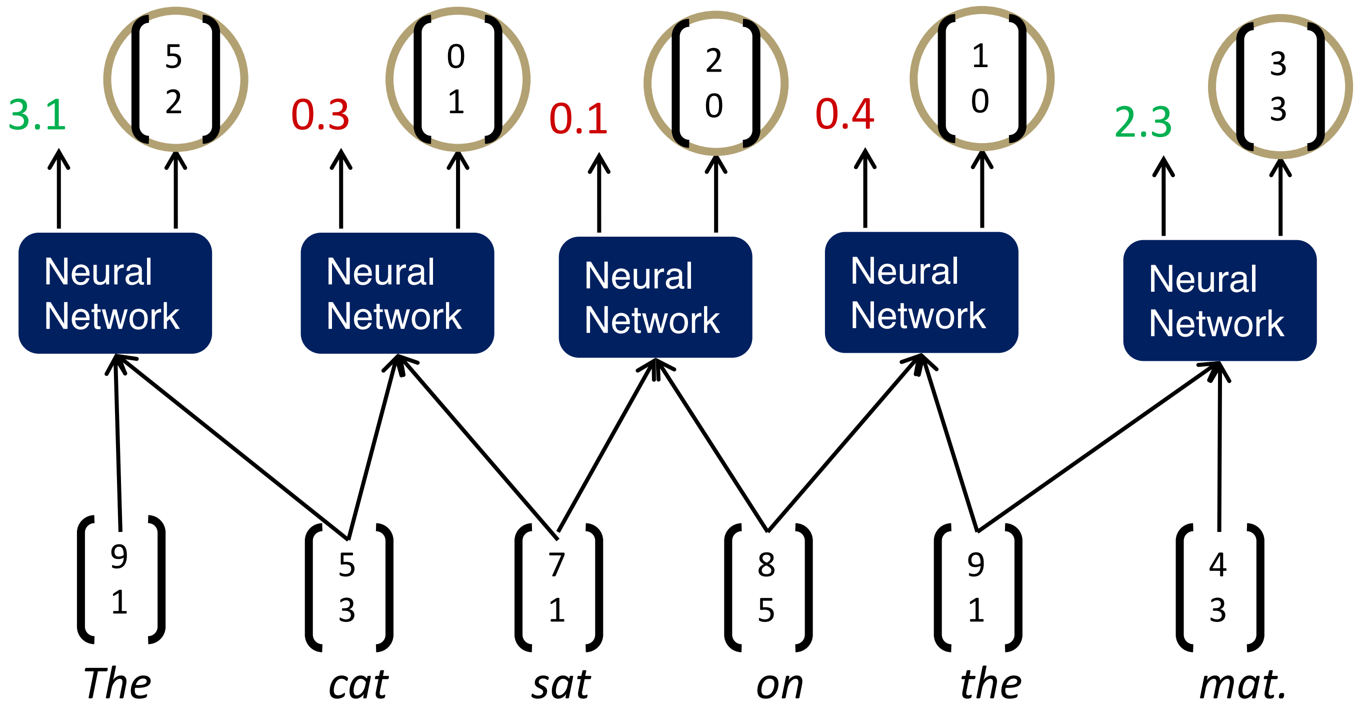
$$\text{score} = U^{\mathsf{T}} p$$

$$\boxed{p = \tanh\left(W\begin{bmatrix}c_1\\c_2\end{bmatrix} + b\right),}$$

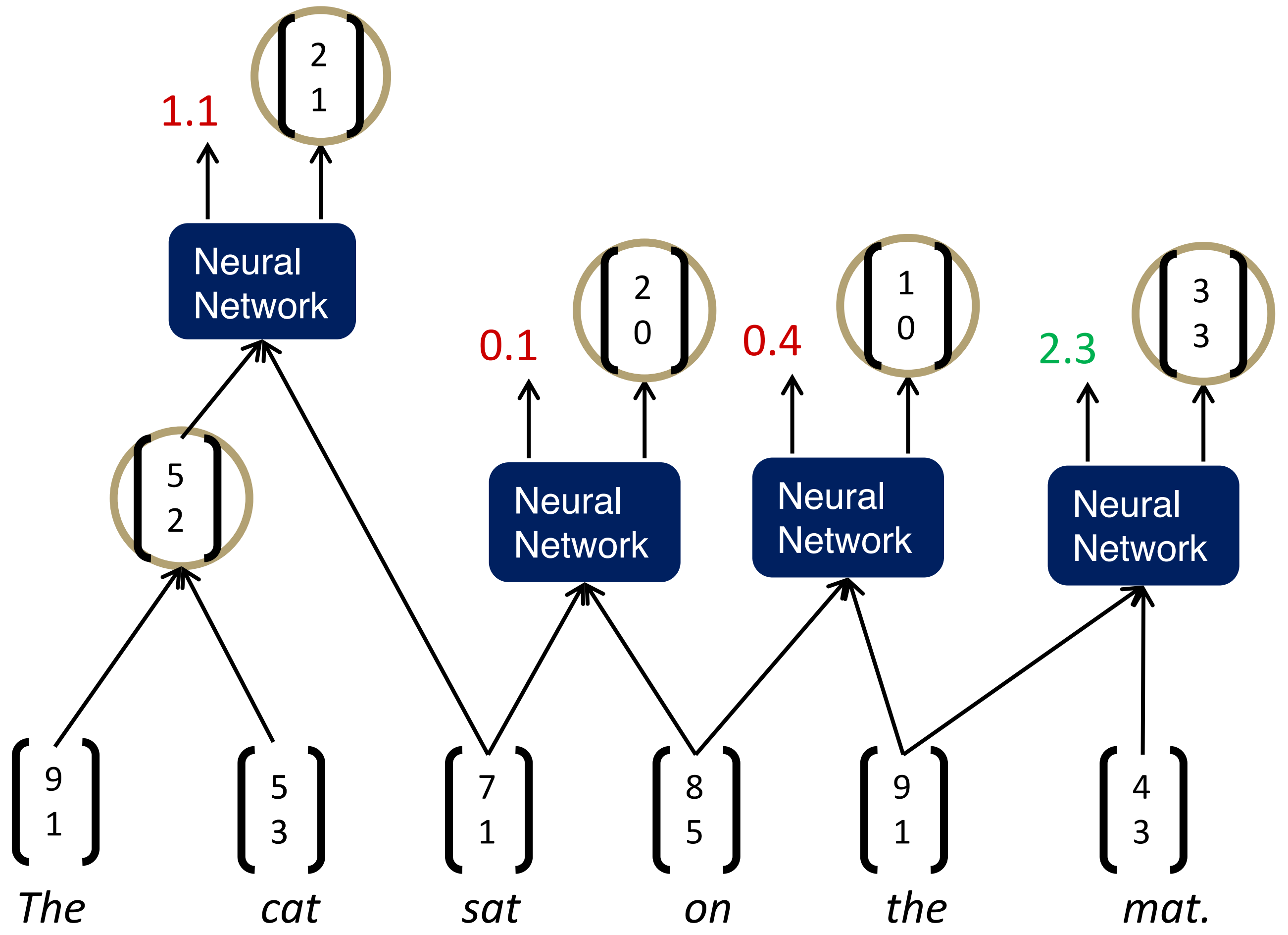
Same *W* parameters at all nodes of the tree



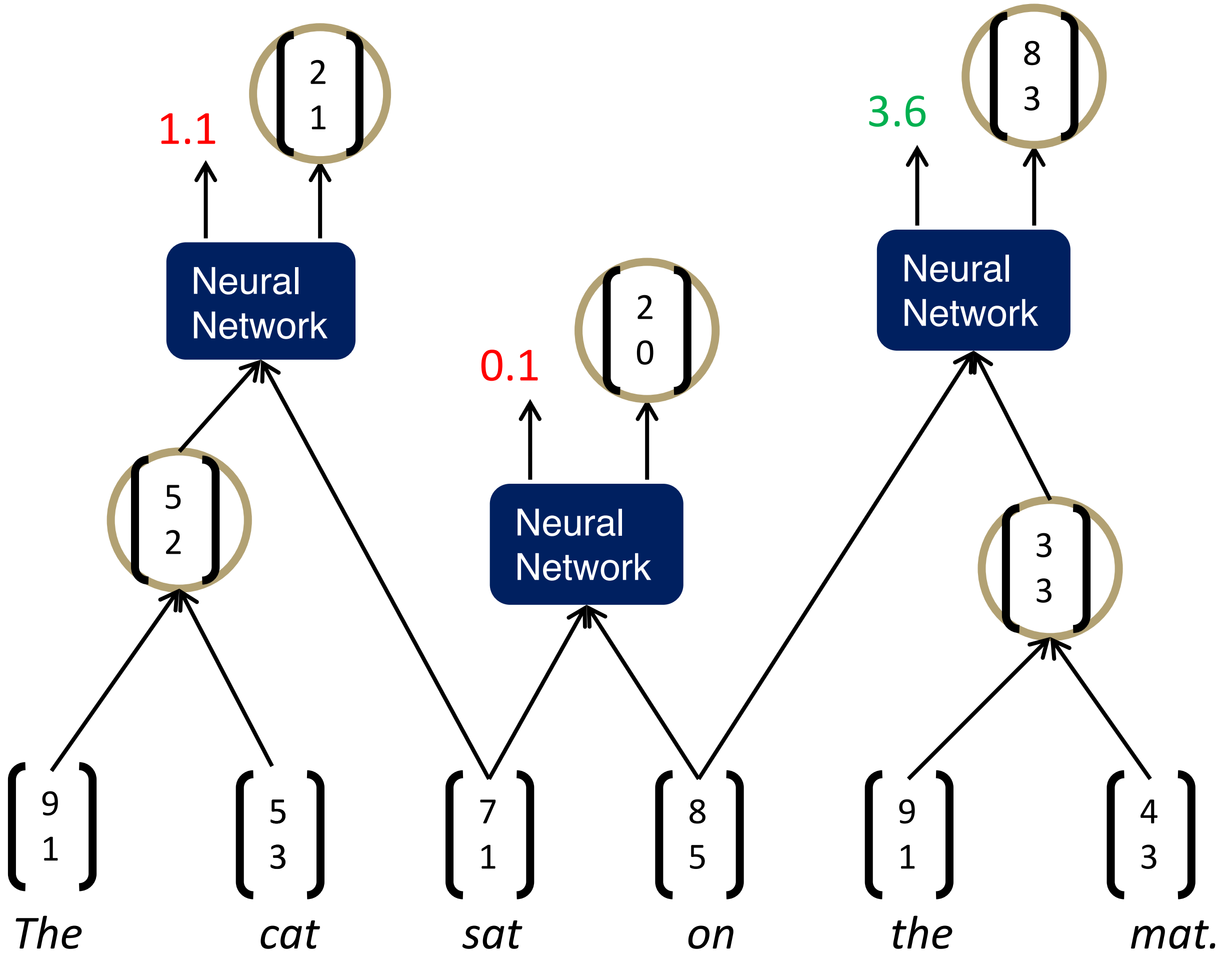
Parsing a sentence with an RNN



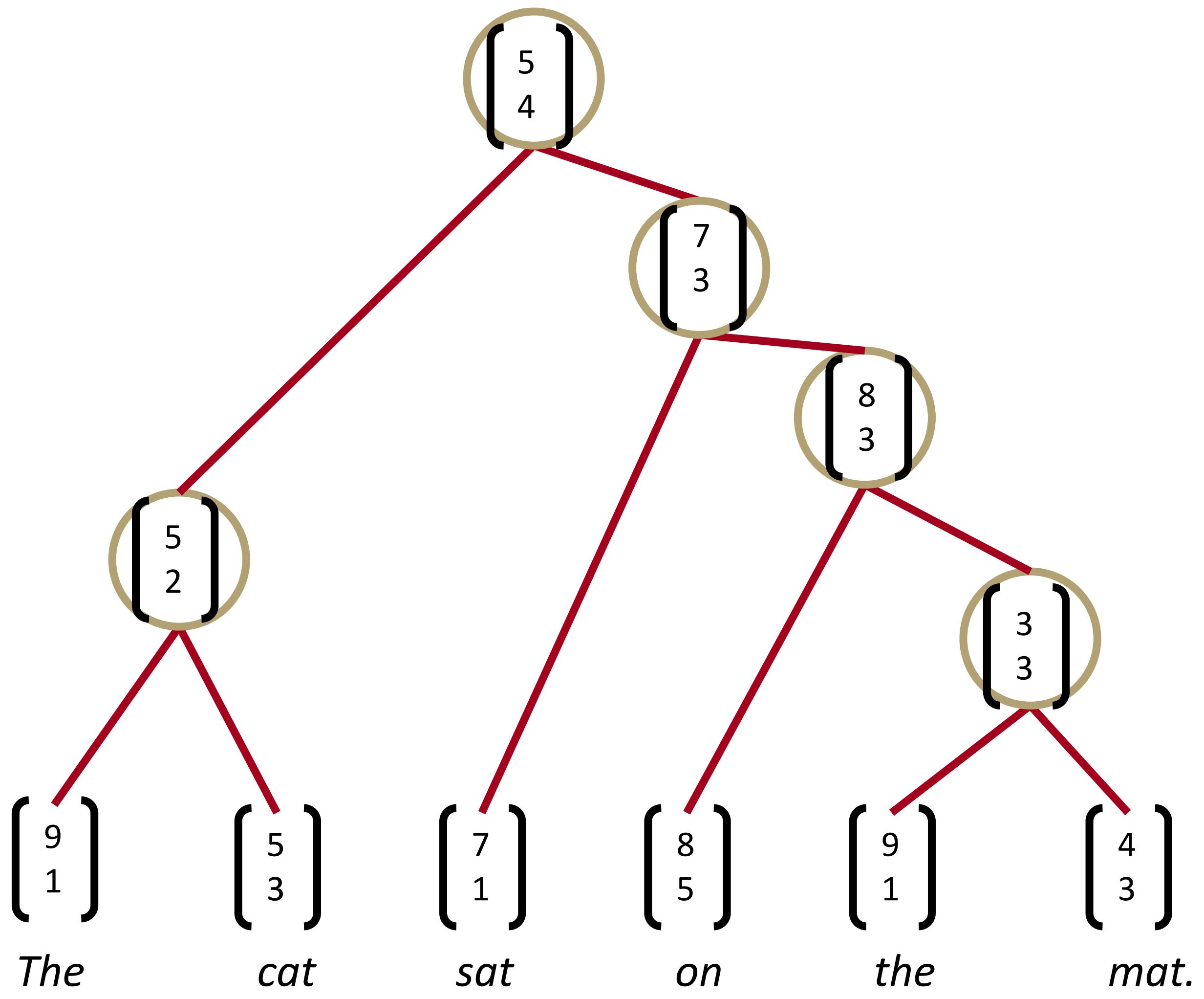
Parsing a sentence



Parsing a sentence



Parsing a sentence

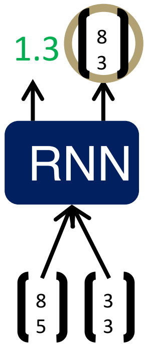


$\begin{bmatrix}5\\4\end{bmatrix}$
$\begin{bmatrix}7\\3\end{bmatrix}$
$\begin{bmatrix}8\\3\end{bmatrix}$
$\begin{bmatrix}5\\2\end{bmatrix}$
$\begin{bmatrix}3\\3\end{bmatrix}$
$\begin{bmatrix}9\\1\end{bmatrix}$
$\begin{bmatrix}5\\3\end{bmatrix}$
$\begin{bmatrix}7\\1\end{bmatrix}$
$\begin{bmatrix}8\\5\end{bmatrix}$
$\begin{bmatrix}9\\1\end{bmatrix}$
$\begin{bmatrix}4\\3\end{bmatrix}$
The
cat
sat
on
the
mat.

Max-Margin Framework - Details

- The score of a tree is computed by the sum of the parsing decision scores at each node:

$$s(x, y) = \sum_{n \in nodes(y)} s_n$$



- *x* is sentence; *y* is parse tree

Max-Margin Framework - Details

- Similar to max-margin parsing (Taskar et al. 2004), a supervised max-margin objective

$$J = \sum_i s(x_i, y_i) - \max_{y \in A(x_i)} \left(s(x_i, y) + \Delta(y, y_i) \right)$$

- The loss $\Delta(y, y_i)$ penalizes all incorrect decisions
- Structure search for A(x) was greedy (join best nodes each time)
    - Instead: Beam search with chart

Backpropagation Through Structure

Introduced by Goller & Küchler (1996)

Principally the same as general backpropagation

$$\boxed{\delta^{(l)} = \left((W^{(l)})^T \delta^{(l+1)}\right) \circ f'(z^{(l)}),}$$

$$\boxed{\frac{\partial}{\partial W^{(l)}} E_R = \delta^{(l+1)} (a^{(l)})^T + \lambda W^{(l)}}$$

Three differences resulting from the recursion and tree structure:

1. Sum derivatives of *W* from all nodes (like RNN)
2. Split derivatives at each node (for tree)
3. Add error messages from parent + node itself

BTS: 1) Sum derivatives of all nodes

You can actually assume it's a different *W* at each node

Intuition via example:

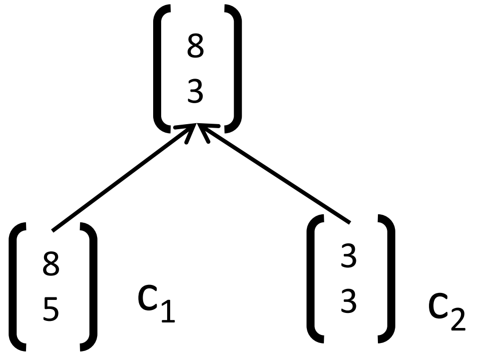
$$
\begin{aligned}
& \frac{\partial}{\partial W} f(W(f(Wx)) \\
= \quad & f'(W(f(Wx)) \left(\left(\frac{\partial}{\partial W} W \right) f(Wx) + W \frac{\partial}{\partial W} f(Wx) \right) \\
= \quad & f'(W(f(Wx)) \left(f(Wx) + W f'(Wx)x \right)
\end{aligned}
$$

If we take separate derivatives of each occurrence, we get same:

$$
\begin{aligned}
& \frac{\partial}{\partial W_2} f(W_2(f(W_1x)) + \frac{\partial}{\partial W_1} f(W_2(f(W_1x)) \\
= \quad & f'(W_2(f(W_1x)) \left(f(W_1x) \right) + f'(W_2(f(W_1x)) \left(W_2 f'(W_1x)x \right) \\
= \quad & f'(W_2(f(W_1x)) \left(f(W_1x) + W_2 f'(W_1x)x \right) \\
= \quad & f'(W(f(Wx)) \left(f(Wx) + W f'(Wx)x \right)
\end{aligned}
$$

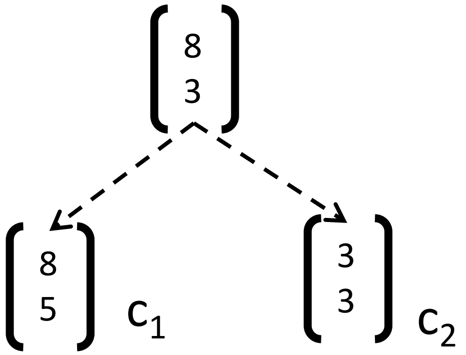
BTS: 2) Split derivatives at each node

During forward prop, the parent is computed using 2 children



$$p = \tanh\left(W\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} + b\right)$$

Hence, the errors need to be computed wrt each of them:

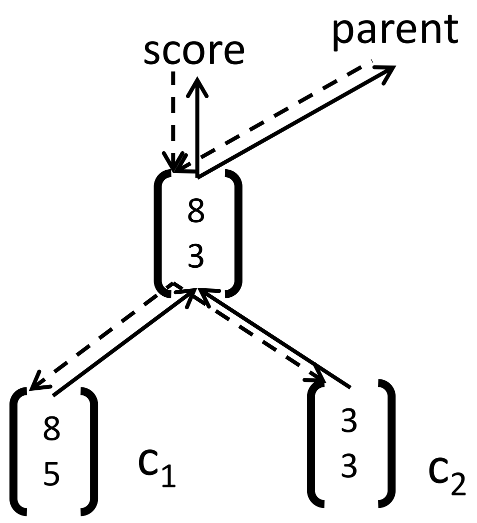


where each child's error is *n*-dimensional

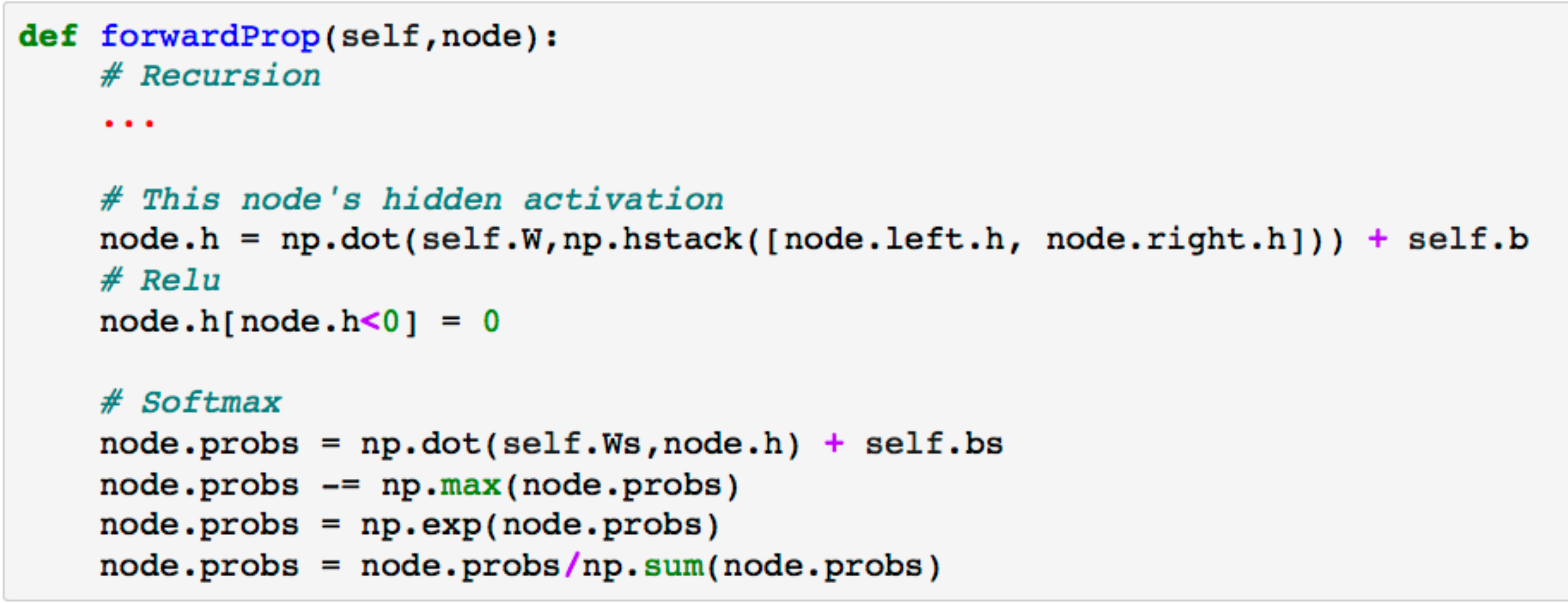
$$\delta_{p \to c_1 c_2} = [\delta_{p \to c_1} \delta_{p \to c_2}]$$

BTS: 3) Add error messages

- At each node:
  - What came up (fprop) must come down (bprop)
  - Total error messages = error messages from parent + error message from own score



BTS Python Code: forwardProp



```
def forwardProp(self,node):
    # Recursion
    ...

    # This node's hidden activation
    node.h = np.dot(self.W,np.hstack([node.left.h, node.right.h])) + self.b
    # Relu
    node.h[node.h<0] = 0

    # Softmax
    node.probs = np.dot(self.Ws,node.h) + self.bs
    node.probs -= np.max(node.probs)
    node.probs = np.exp(node.probs)
    node.probs = node.probs/np.sum(node.probs)
```

BTS Python Code: backProp

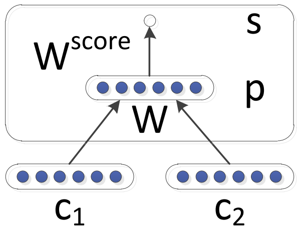
```
def backProp(self,node,error=None):
    # Softmax grad
    deltas = node.probs
    deltas[node.label] -= 1.0
    self.dWs += np.outer(deltas,node.h)
    self.dbs += deltas
    deltas = np.dot(self.Ws.T,deltas)

    # Add deltas from above
    if error is not None:
        deltas += error

    # f'(z) now:
    deltas *= (node.h != 0)

    # Update word vectors if leaf node:
    if node.isLeaf:
        self.dL[node.word] += deltas
        return

    # Recursively backprop
    if not node.isLeaf:
        self.dW += np.outer(deltas,np.hstack([node.left.h, node.right.h]))
        self.db += deltas
        # Error signal to children
        deltas = np.dot(self.W.T, deltas)
        self.backProp(node.left, deltas[:self.hiddenDim])
        self.backProp(node.right, deltas[self.hiddenDim:])
```

$$\boxed{\delta^{(l)} = \left((W^{(l)})^T \delta^{(l+1)}\right) \circ f'(z^{(l)}),}$$

$$\boxed{\frac{\partial}{\partial W^{(l)}} E_R = \delta^{(l+1)} (a^{(l)})^T + \lambda W^{(l)}}$$

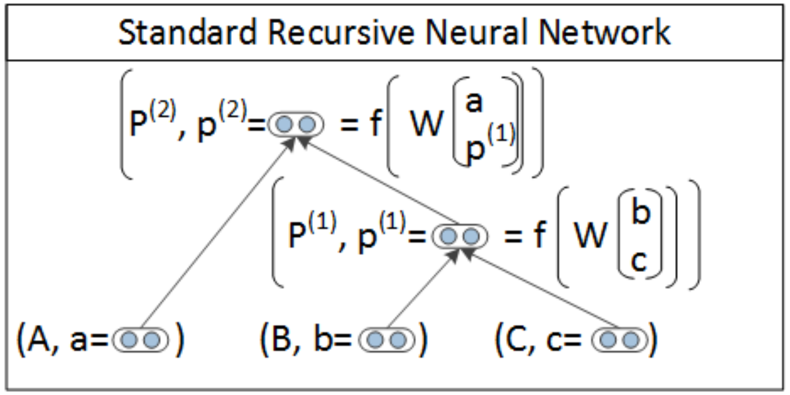
Discussion: Simple RNN

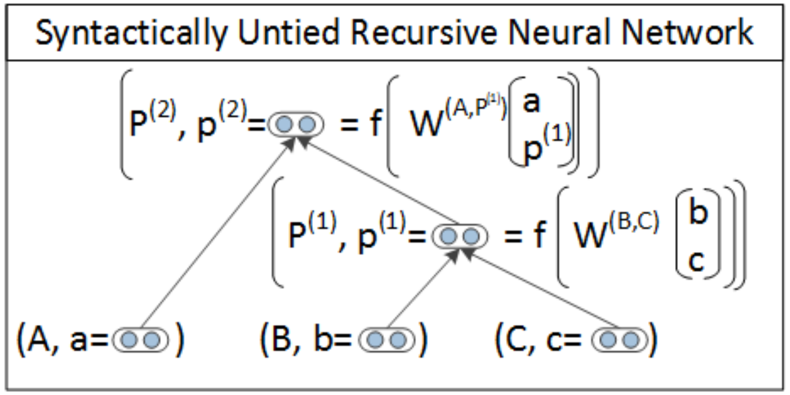
- Decent results with single matrix TreeRNN
- Single weight matrix TreeRNN could capture some phenomena but not adequate for more complex, higher order composition and parsing long sentences
- There is no real interaction between the input words
- The composition function is the same for all syntactic categories, punctuation, etc.



Version 2: Syntactically-Untied RNN

- A symbolic Context-Free Grammar (CFG) backbone is adequate for basic syntactic structure
- We use the discrete syntactic categories of the children to choose the composition matrix
- A TreeRNN can do better with different composition matrix for different syntactic environments
- The result gives us a better semantics




Syntactically Untied Recursive Neural Network
P(2), p(2)= = f W(A,P(1)) a p(1)
P(1), p(1)= = f W(B,C) b c
(A, a=)
(B, b=)
(C, c=)

Compositional Vector Grammars

- Problem: Speed. Every candidate score in beam search needs a matrix-vector product.

- Solution: Compute score only for a subset of trees coming from a simpler, faster model (PCFG)
  - Prunes very unlikely candidates for speed
  - Provides coarse syntactic categories of the children for each beam candidate

- Compositional Vector Grammar = PCFG + TreeRNN

Related Work for parsing

- Resulting CVG Parser is related to previous work that extends PCFG parsers
- Klein and Manning (2003a) : manual feature engineering
- Petrov et al. (2006) : learning algorithm that splits and merges syntactic categories
- Lexicalized parsers (Collins, 2003; Charniak, 2000): describe each category with a lexical item
- Hall and Klein (2012) combine several such annotation schemes in a factored parser.
- CVGs extend these ideas from discrete representations to richer continuous ones

Experiments

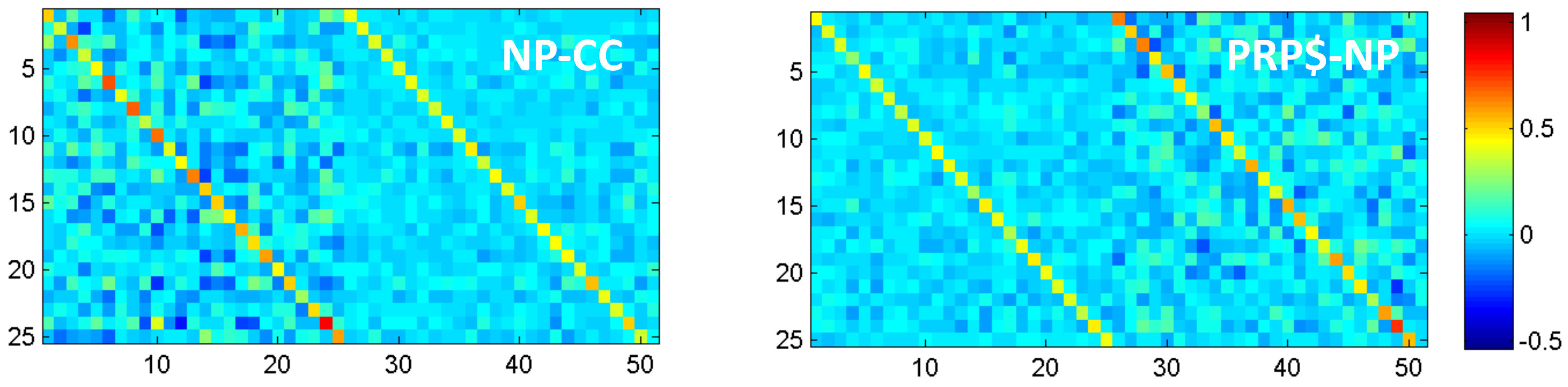
- Standard *WSJ* split, labeled F1
- Based on simple PCFG with fewer states
- Fast pruning of search space, few matrix-vector products
- 3.8% higher F1, 20% faster than Stanford factored parser

Parser	Test, All Sentences
Stanford PCFG, (Klein and Manning, 2003a)	85.5
Stanford Factored (Klein and Manning, 2003b)	86.6
Factored PCFGs (Hall and Klein, 2012)	89.4
Collins (Collins, 1997)	87.7
SSN (Henderson, 2004)	89.4
Berkeley Parser (Petrov and Klein, 2007)	90.1
CVG (RNN) (Socher et al., ACL 2013)	85.0
CVG (SU-RNN) (Socher et al., ACL 2013)	90.4
Charniak - Self Trained (McClosky et al. 2006)	91.0
Charniak - Self Trained-ReRanked (McClosky et al. 2006)	92.1

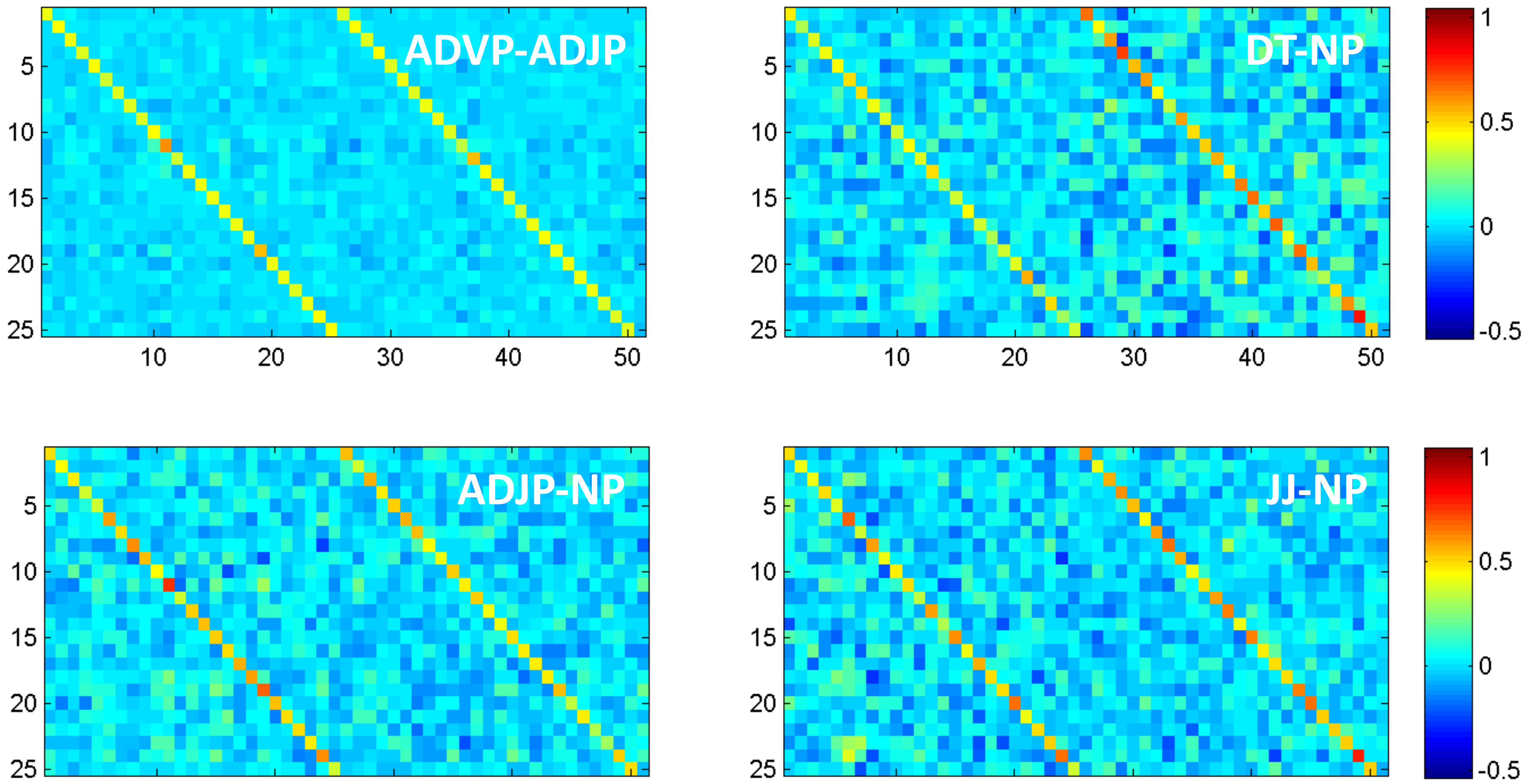
SU-RNN / CVG [Socher, Bauer, Manning, Ng 2013]

Learns soft notion of head words

Initialization: $W^{(\cdot\cdot)} = 0.5[I_{n\times n} I_{n\times n} 0_{n\times 1}] + \epsilon$



SU-RNN / CVG [Socher, Bauer, Manning, Ng 2013]



Analysis of resulting vector representations

All the figures are adjusted for seasonal variations

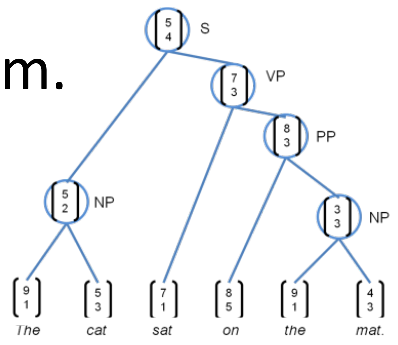
1. All the numbers are adjusted for seasonal fluctuations
2. All the figures are adjusted to remove usual seasonal patterns

Knight-Ridder wouldn't comment on the offer

1. Harsco declined to say what country placed the order
2. Coastal wouldn't disclose the terms

Sales grew almost 7% to $UNK m. from $UNK m.

1. Sales rose more than 7% to $94.9 m. from $88.3 m.
2. Sales surged 40% to UNK b. yen from UNK b.



Version 3:
Compositionality Through Recursive Matrix-Vector Spaces

Before:

$$\boxed{p = \tanh\left(W\begin{pmatrix} c_1 \\ c_2 \end{pmatrix} + b\right)}$$

One way to make the composition function more powerful was by untying the weights *W*

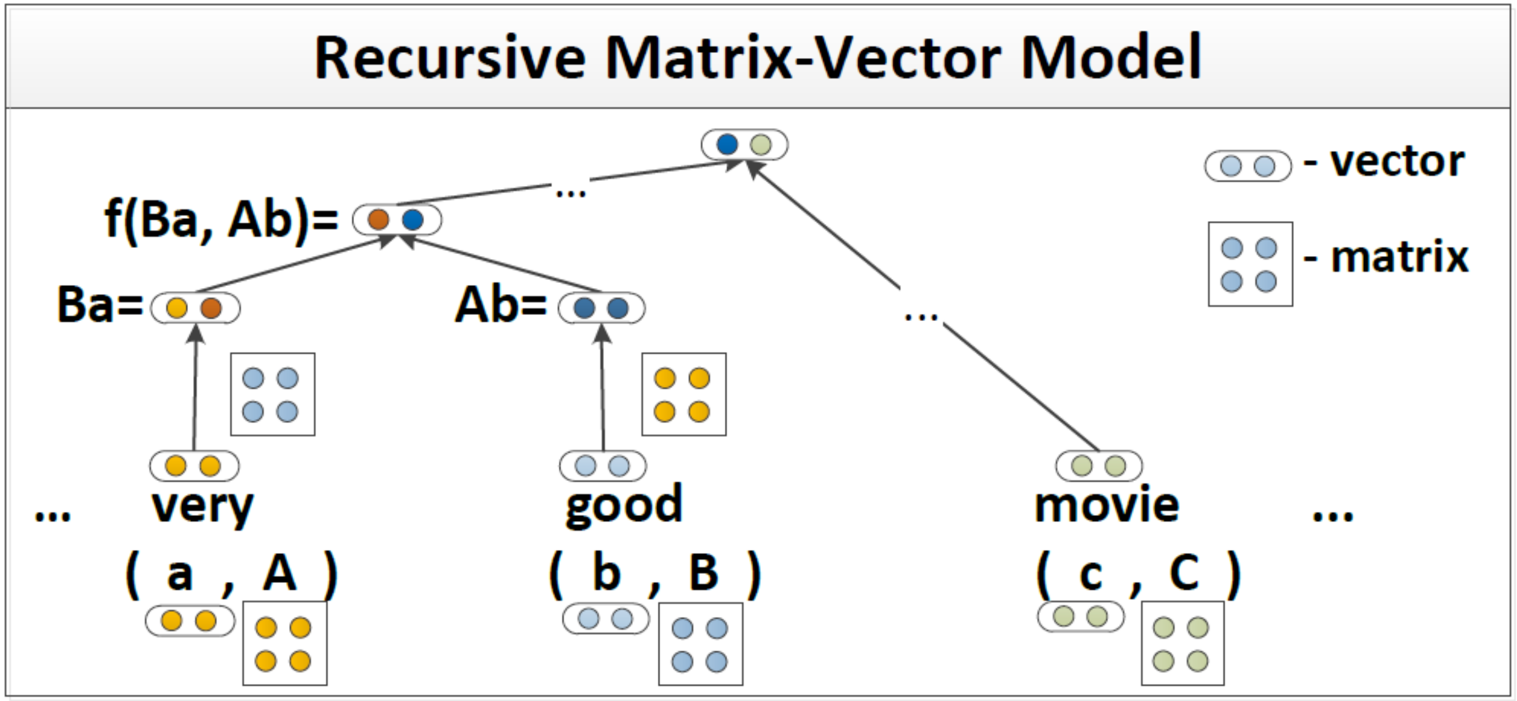
But what if words act mostly as an operator, e.g. "very" in
very good

Proposal: A new composition function

Compositionality Through Recursive Matrix-Vector Recursive Neural Networks

$$p = \tanh\left(W \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} + b\right)$$

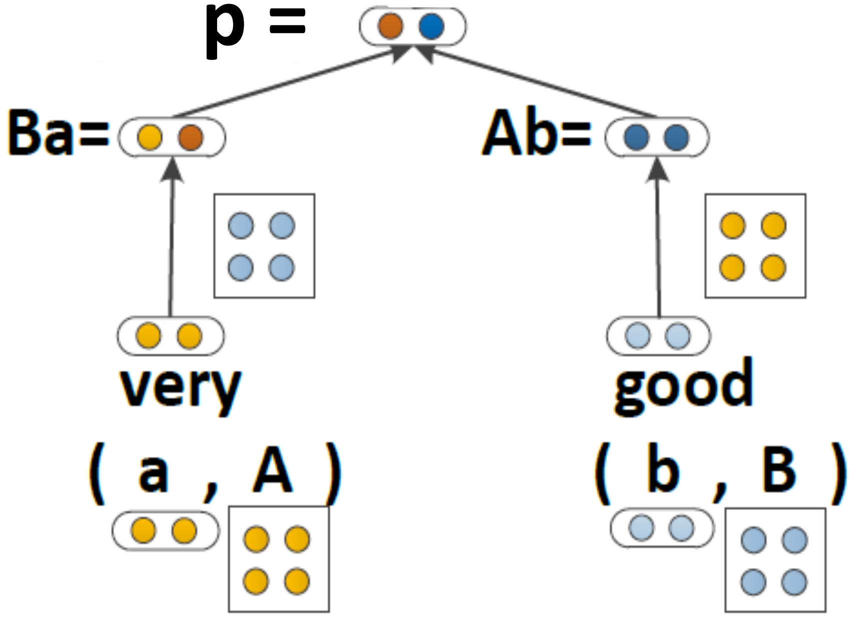
$$\boxed{p = \tanh\left(W \begin{pmatrix} C_2 c_1 \\ C_1 c_2 \end{pmatrix} + b\right)}$$



Matrix-vector RNNs

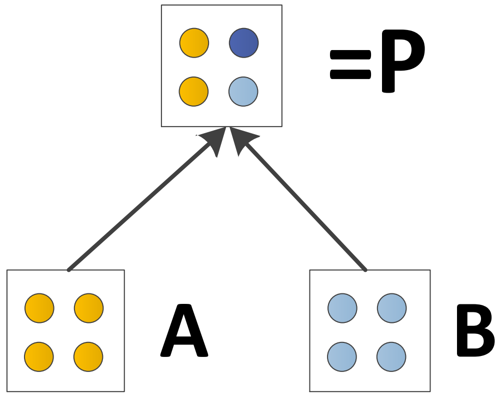
[Socher, Huval, Bhat, Manning, & Ng, 2012]

$$p = f\left(W \begin{bmatrix} Ba \\ Ab \end{bmatrix}\right)$$



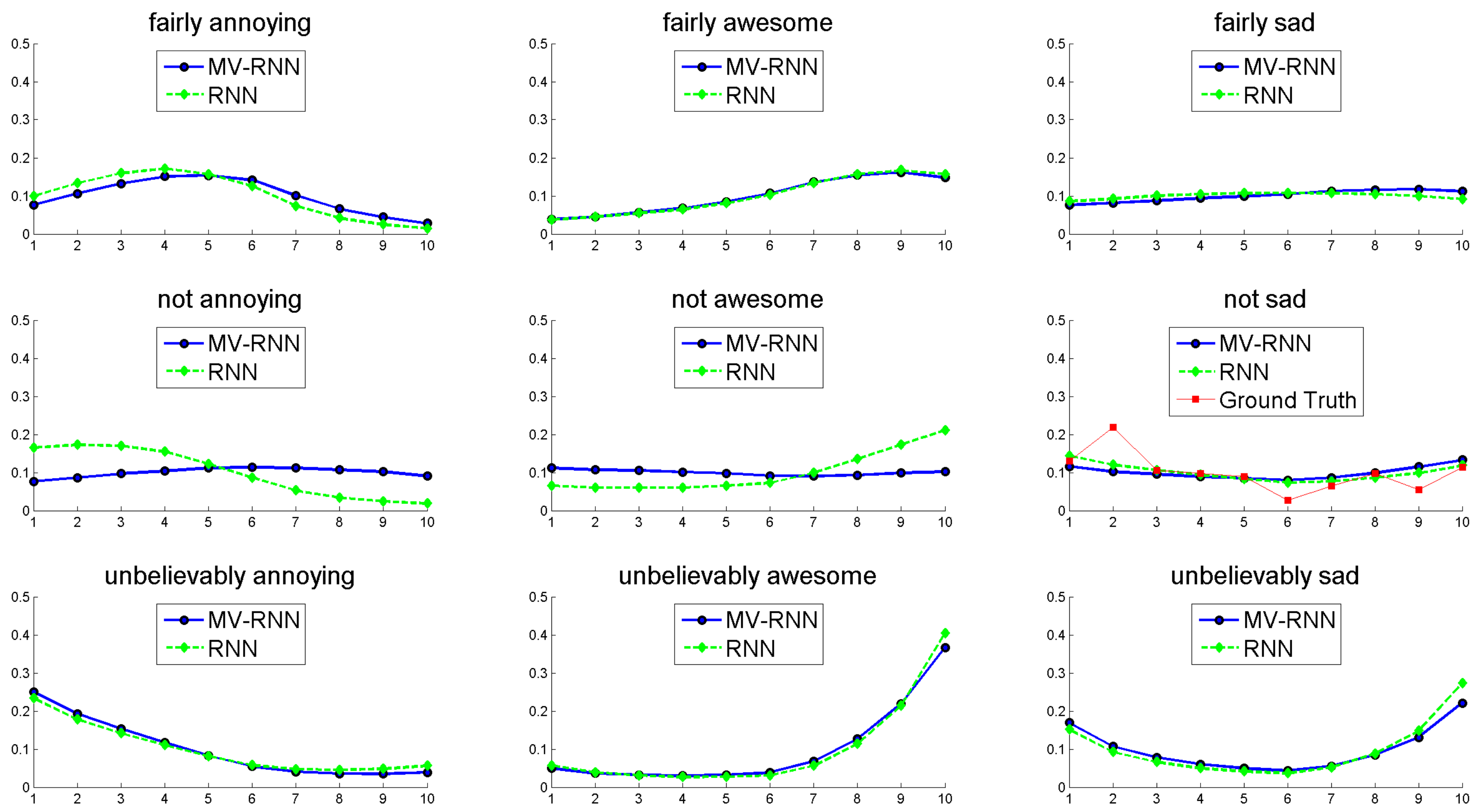
$$\boxed{P = g(A, B) = W_M \begin{bmatrix} A \\ B \end{bmatrix}}$$

$$W_M \in \mathbb{R}^{n \times 2n}$$



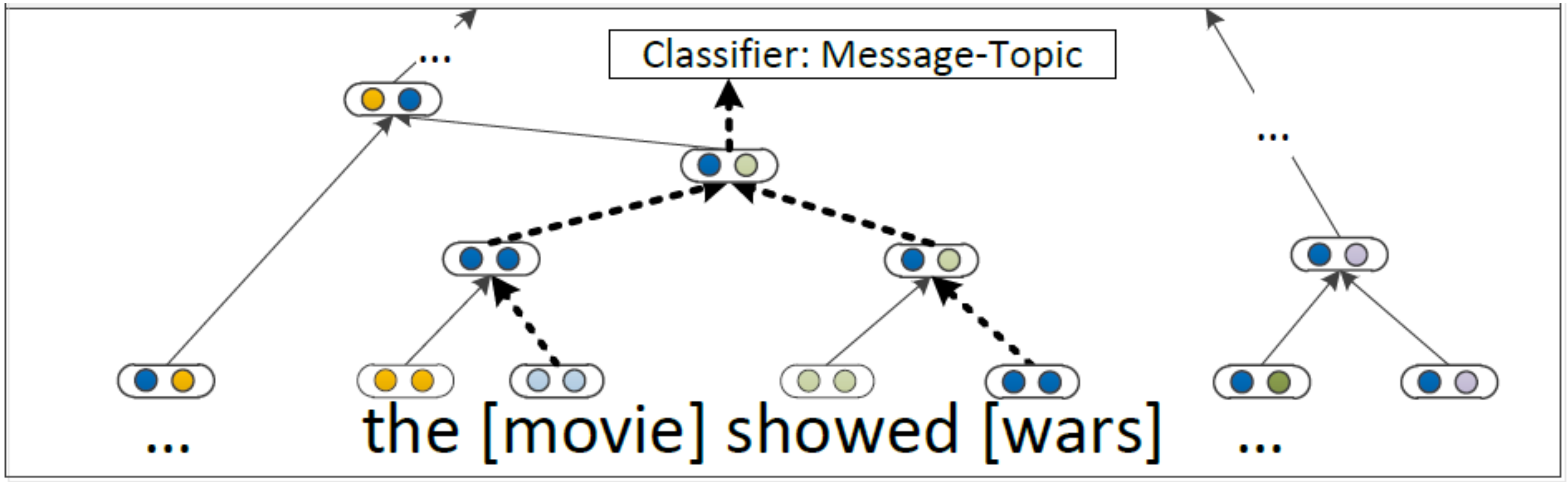
Predicting Sentiment Distributions

Good example for non-linearity in language



Classification of Semantic Relationships

- Can an MV-RNN learn how a large syntactic context conveys a semantic relationship?
- My [apartment]$_{e1}$ has a pretty large [kitchen] $_{e2}$ → component-whole relationship (e2,e1)
- Build a single compositional semantics for the minimal constituent including both terms



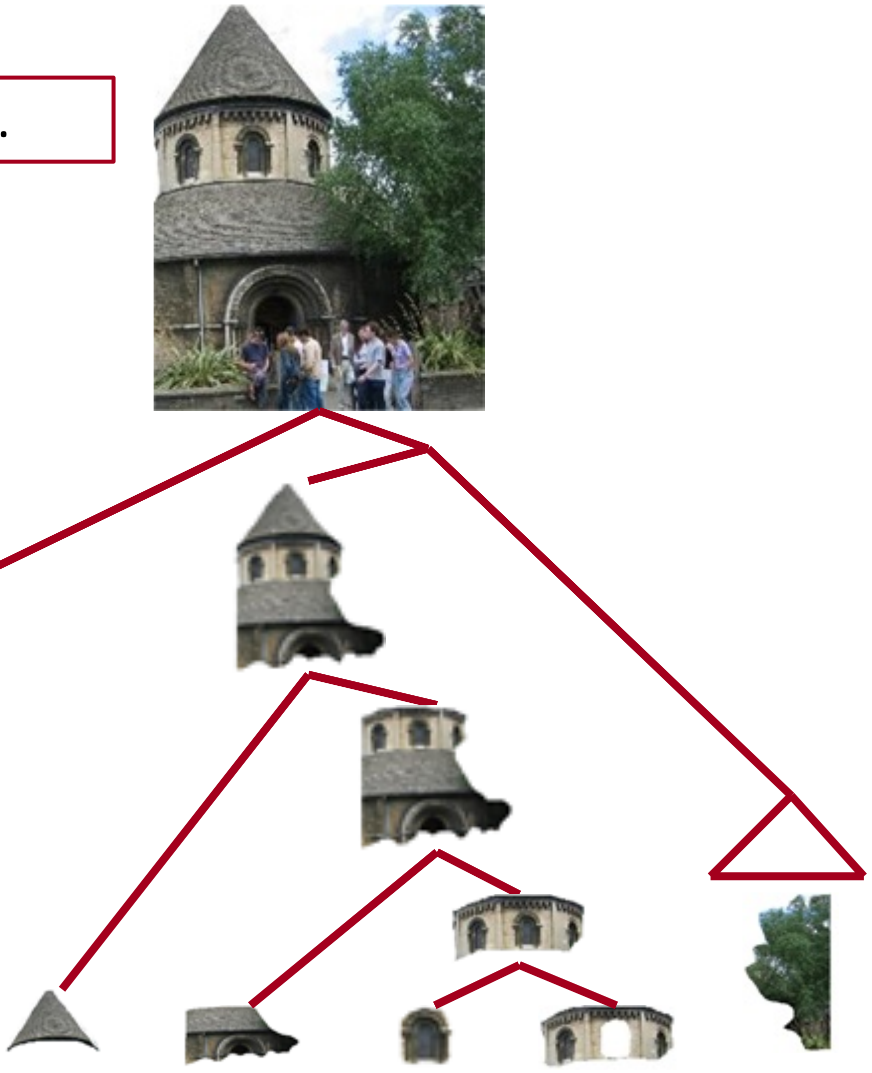
Classification of Semantic Relationships

Classifier	Features	F1
SVM	POS, stemming, syntactic patterns	60.1
MaxEnt	POS, WordNet, morphological features, noun compound system, thesauri, Google n-grams	77.6
SVM	POS, WordNet, prefixes, morphological features, dependency parse features, Levin classes, PropBank, FrameNet, NomLex-Plus, Google n-grams, paraphrases, TextRunner	82.2
RNN	–	74.8
MV-RNN	–	79.1
MV-RNN	**POS, WordNet, NER**	**82.4**

Scene Parsing

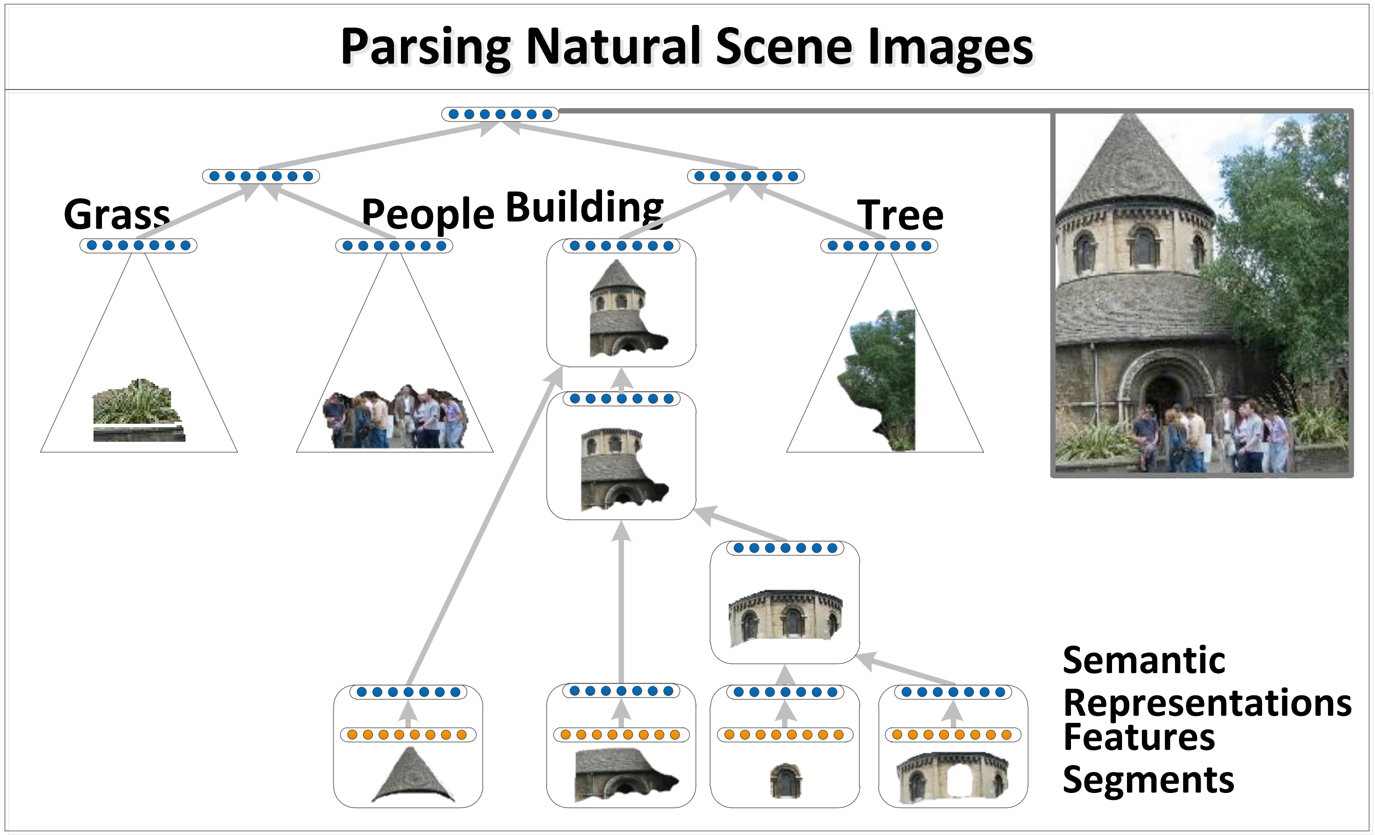
Similar principle of compositionality.

- The meaning of a scene image is also a function of smaller regions,
- how they combine as parts to form larger objects,
- and how the objects interact.

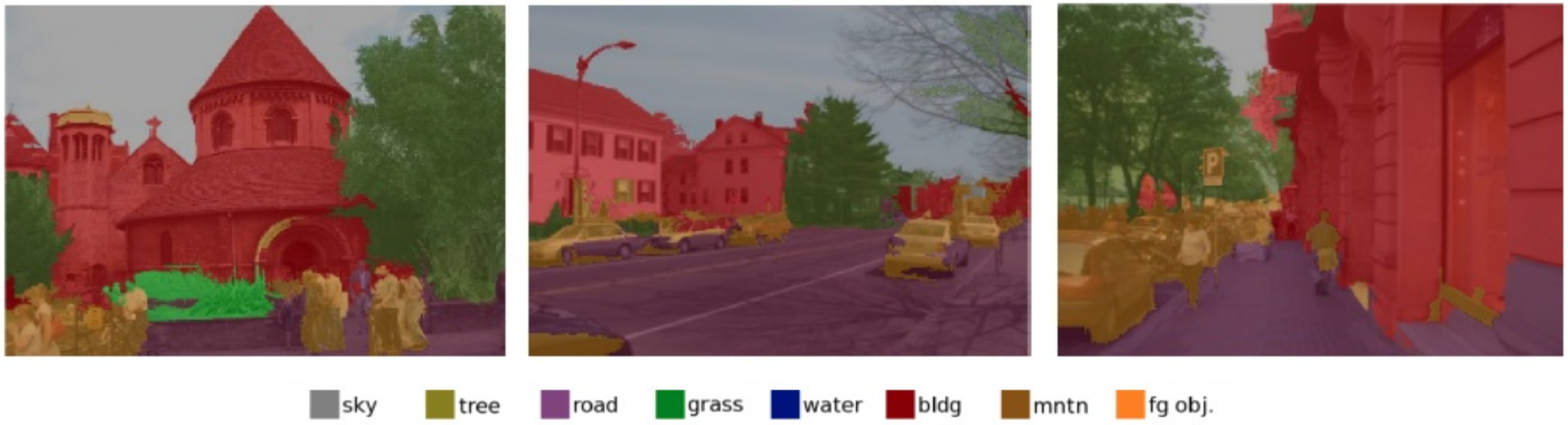


Algorithm for Parsing Images

Same Recursive Neural Network as for natural language parsing!
(Socher et al. ICML 2011)



Multi-class segmentation



Method	Accuracy
Pixel CRF (Gould et al., ICCV 2009)	74.3
Classifier on superpixel features	75.9
Region-based energy (Gould et al., ICCV 2009)	76.4
Local labelling (Tighe & Lazebnik, ECCV 2010)	76.9
Superpixel MRF (Tighe & Lazebnik, ECCV 2010)	77.5
Simultaneous MRF (Tighe & Lazebnik, ECCV 2010)	77.5
Recursive Neural Network	**78.1**

Stanford Background Dataset (Gould et al. 2009)

Next lecture

- Model overview, comparison, extensions, combinations, etc