Recursive Neural Network

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Applied Deep Learning

YUN-NUNG (VIVIAN) CHEN

WWW.CSIE.NTU.EDU.TW/~YVCHEN/F105-ADL

National Taiwan University

Slide credit from Richard Socher

Sequence Modeling

Idea: aggregate the meaning from all words into a vector

→ ***Compositionality***

Method:

- Basic combination: average, sum
- Neural combination:
  - ✓Recursive neural network (RvNN)
  - ✓Recurrent neural network (RNN)
  - ✓Convolutional neural network (CNN)

N-dim

這 (this) $\begin{bmatrix} 0.2 & 0.6 & 0.3 & \cdots & 0.4 \end{bmatrix}$

規格 (specification) $\begin{bmatrix} 0.9 & 0.8 & 0.1 & \cdots & 0.1 \end{bmatrix}$

有 (have) $\begin{bmatrix} 0.1 & 0.3 & 0.1 & \cdots & 0.7 \end{bmatrix}$

誠意 (sincerity) $\begin{bmatrix} 0.5 & 0.0 & 0.6 & \cdots & 0.4 \end{bmatrix}$

How to compute $\vec{x} = \begin{bmatrix} x_1 & x_2 & x_3 & \cdots & x_N \end{bmatrix}$

Recursive Neural Network

From Words to Phrases

Recursive Neural Network

Idea: leverage the linguistic knowledge (syntax) for combining multiple words into phrases

Assumption: language is described recursively

Related Work for RvNN

Pollack (1990): Recursive auto-associative memories

Previous Recursive Neural Networks work by Goller & Küchler (1996), Costa et al. (2003) assumed fixed tree structure and used one-hot vectors.

Hinton (1990) and Bottou (2011): Related ideas about recursive models and recursive operators as smooth versions of logic operations

Outline

Property
- Syntactic Compositionality
- Recursion Assumption

Network Architecture and Definition
- Standard Recursive Neural Network
  - Weight-Tied
  - Weight-Untied
- Matrix-Vector Recursive Neural Network
- Recursive Neural Tensor Network

Applications
- Parsing
- Paraphrase Detection
- Sentiment Analysis

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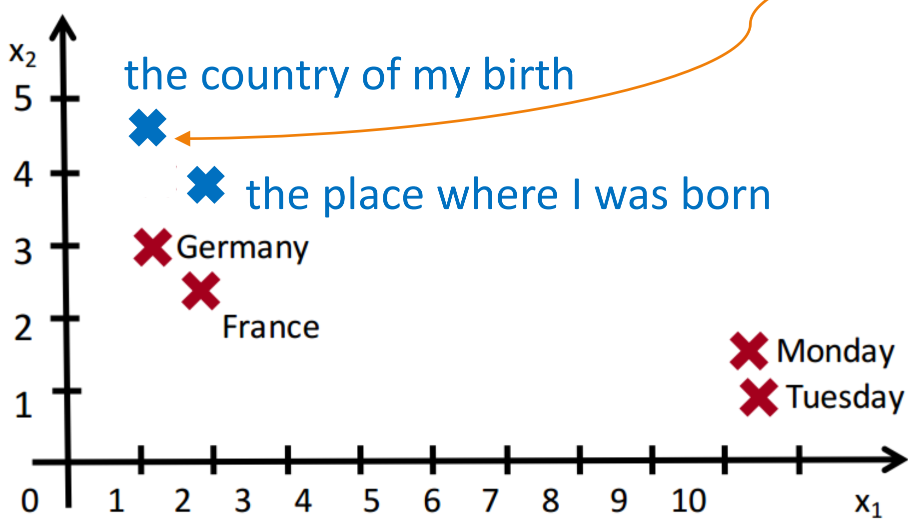
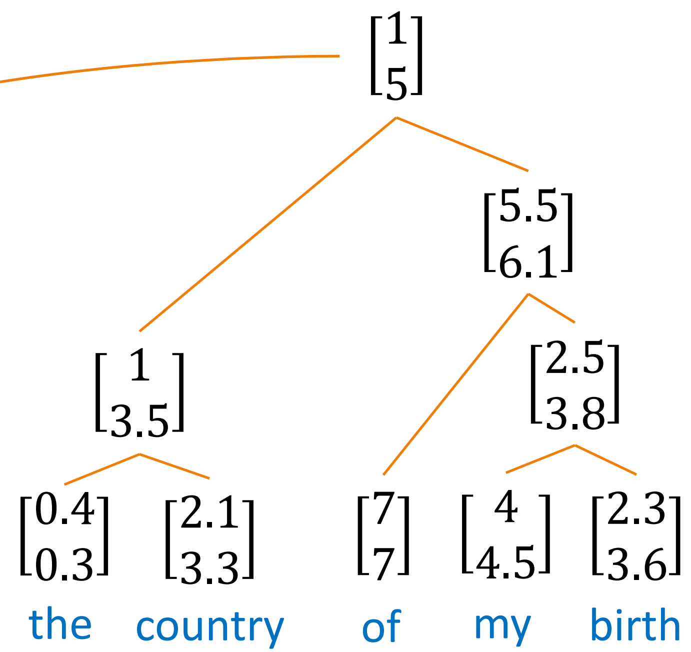
Phrase Mapping

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





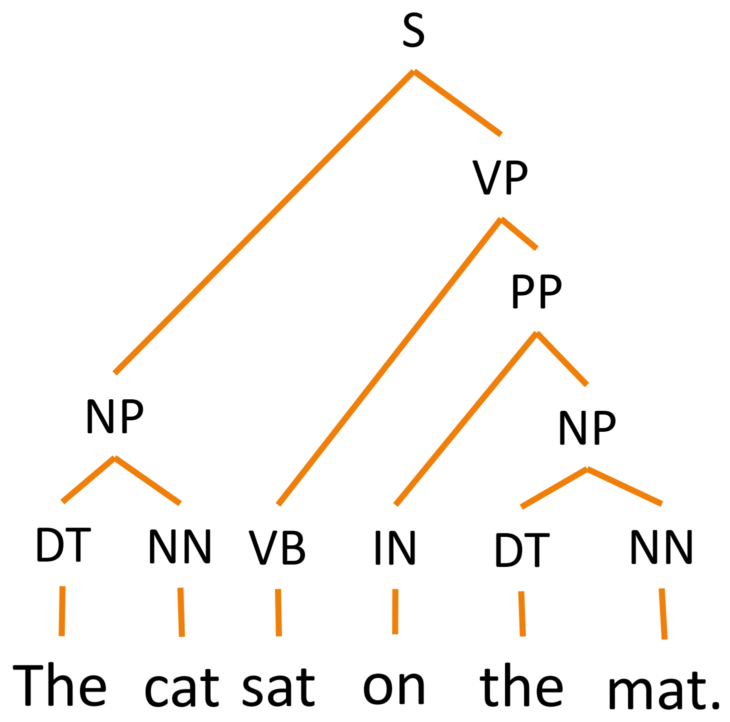
Idea: jointly learn parse trees and compositional vector representations

Sentence Syntactic Parsing

Parsing is a process of analyzing a string of symbols

Parsing tree conveys

1) Part-of-speech for each word
2) Phrases
3) Relationships



(NN = noun, VB = verb, DT = determiner, IN = Preposition)

Sentence Syntactic Parsing

Parsing is a process of analyzing a string of symbols

Parsing tree conveys

1) **Part-of-speech for each word**
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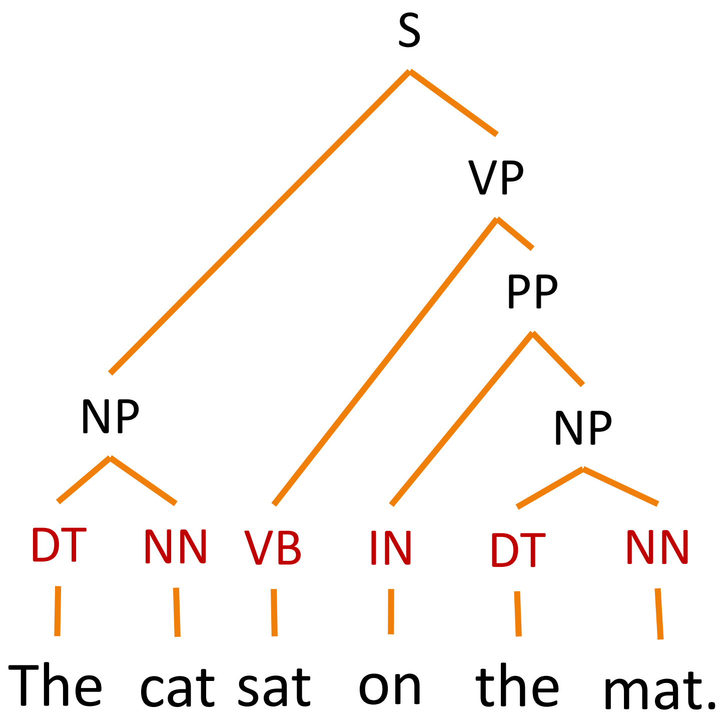

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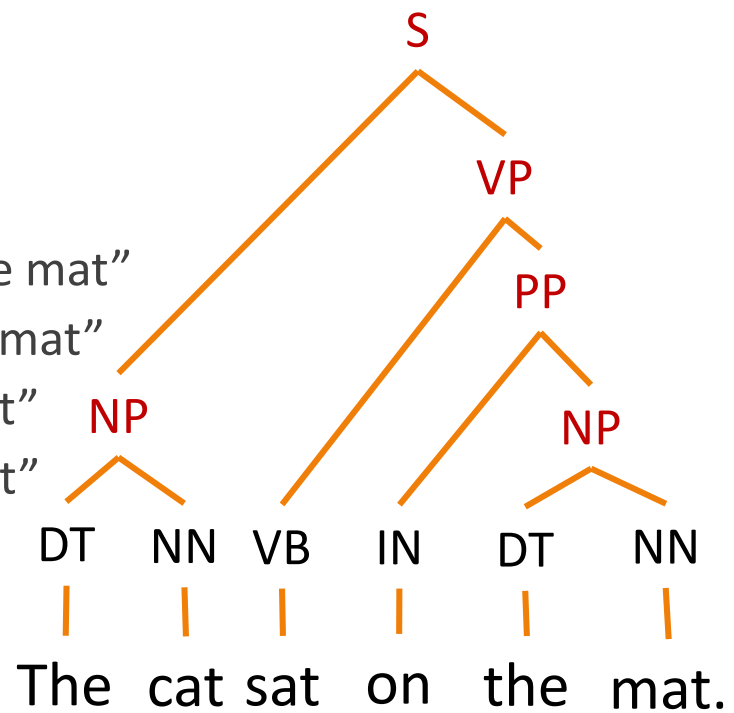
Sentence Syntactic Parsing

Parsing is a process of analyzing a string of symbols

Parsing tree conveys

1) Part-of-speech for each word
2) **Phrases**
   - Noun phrase (NP): “the cat”, “the mat”
   - Preposition phrase (PP): “on the mat”
   - Verb phrase (VP): “sat on the mat”
   - Sentence: “the cat sat on the mat”
3) Relationships



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Sentence Syntactic Parsing

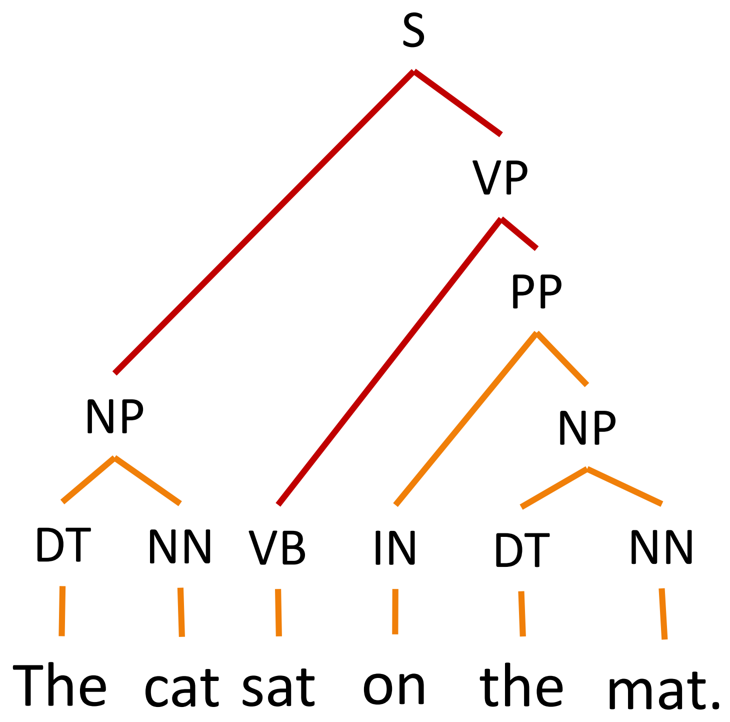
Parsing is a process of analyzing a string of symbols

Parsing tree conveys

1) Part-of-speech for each word
2) Phrases
3) **Relationships**

subject verb modifier_of_place

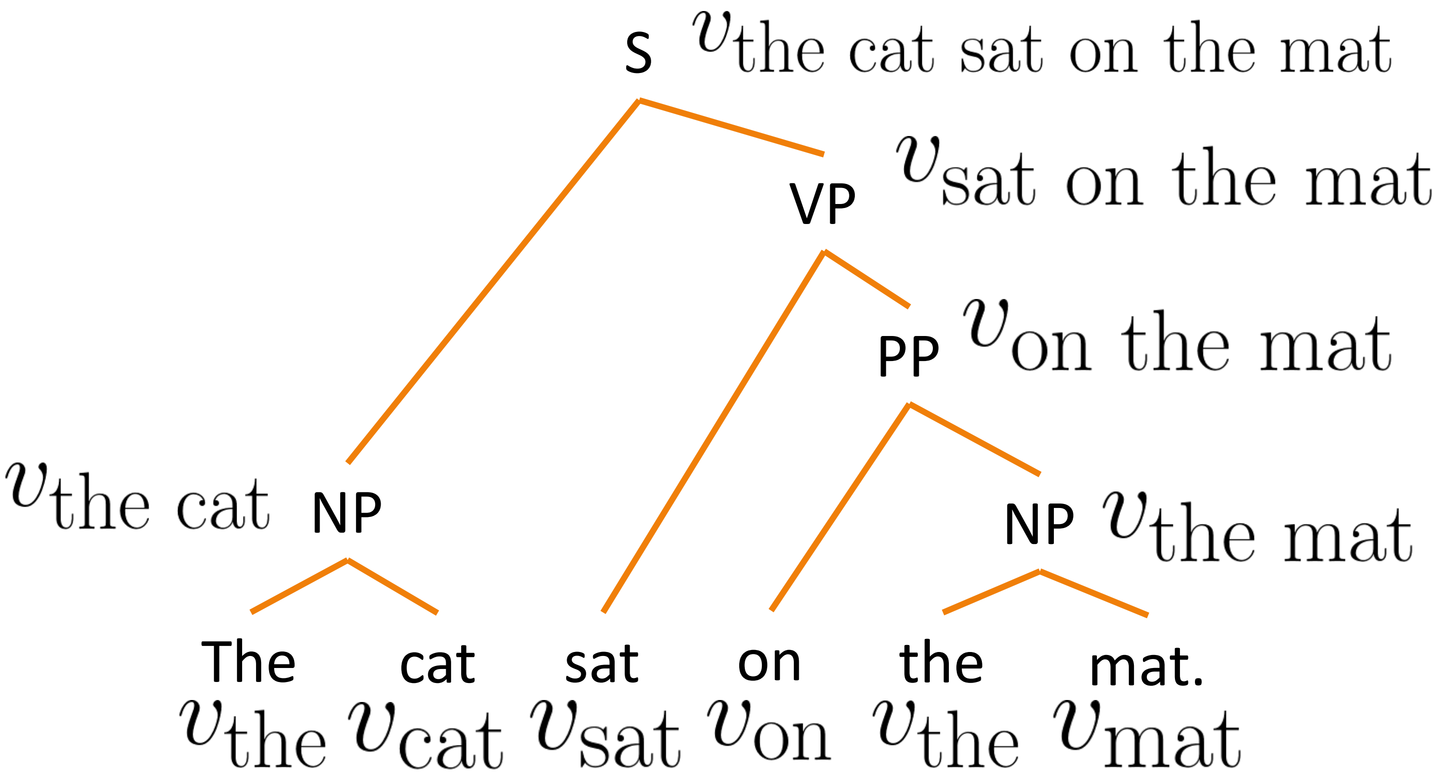
- "the cat" is the subject of "sat"
- "on the mat" is the place modifier of "sat"



(NN = noun, VB = verb, DT = determiner, IN = Preposition)

Learning Structure & Representation

Vector representations incorporate the meaning of words and their compositional structures



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Recursion Assumption

Are languages recursive? debatable

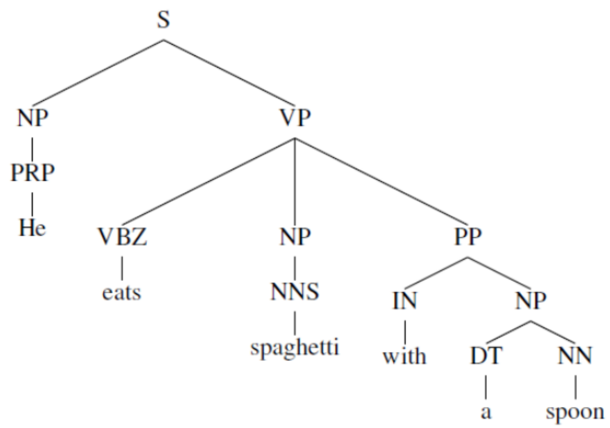
Recursion helps describe natural language

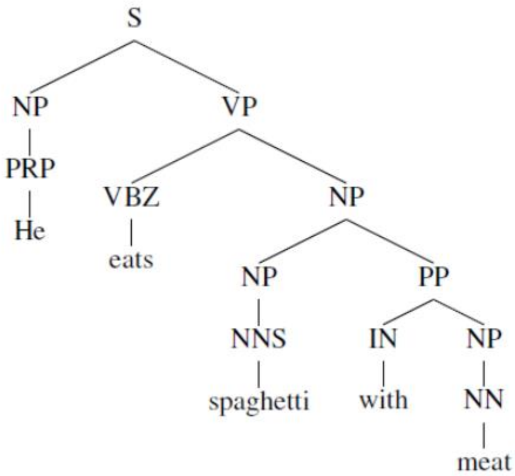
- Ex. “the church which has nice windows”, a noun phrase containing a relative clause that contains a noun phrases
- NP → NP PP

Recursion Assumption

Characteristics of recursion

1. Helpful in disambiguation





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

Language recursion is still up to debate

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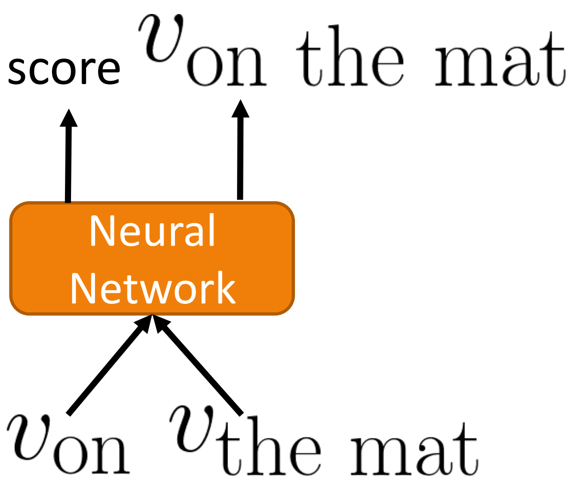
Recursive Neural Network Architecture

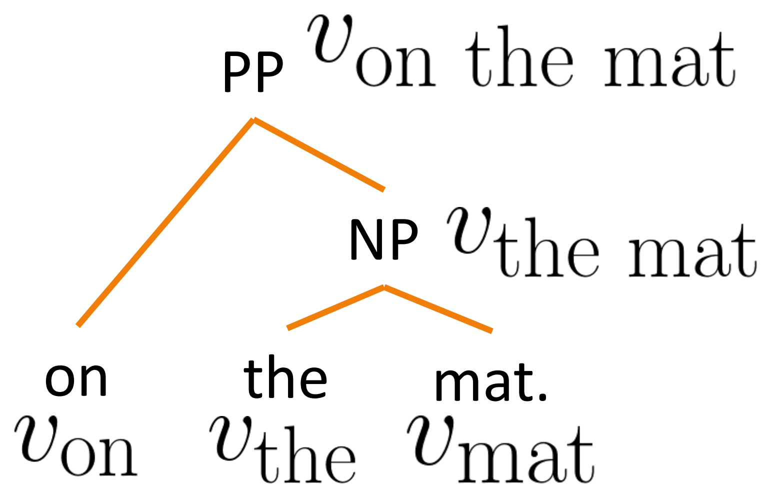
A network is to predict the vectors along with the structure

- Input: two candidate children's vector representations
- Output:

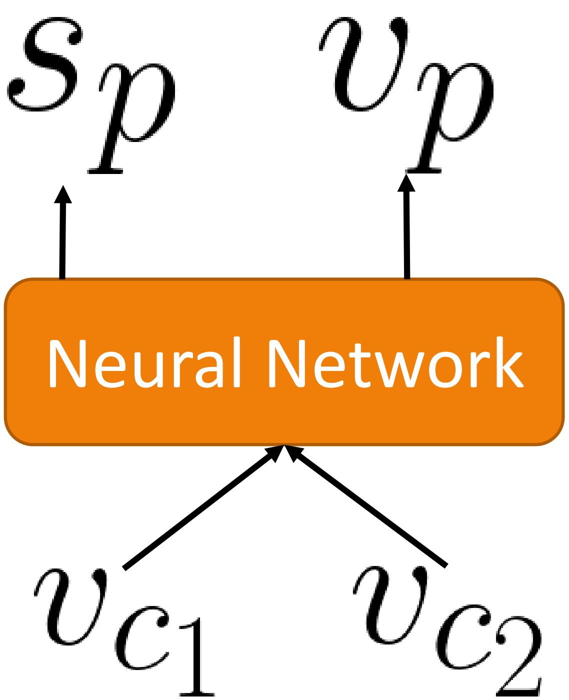
  1) vector representations for the merged node

  2) score of how plausible the new node would be





Recursive Neural Network Definition

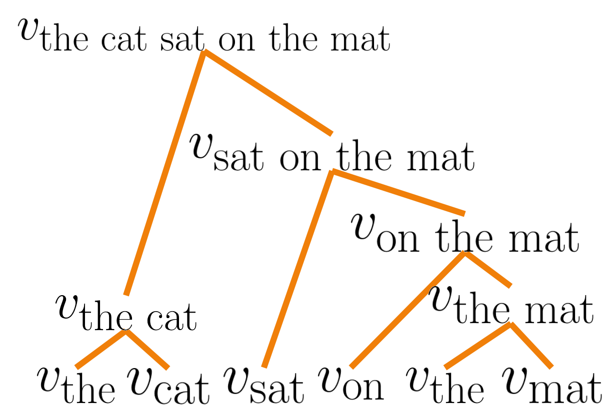


1) vector representations for the merged node

$$v_p = \sigma(W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$

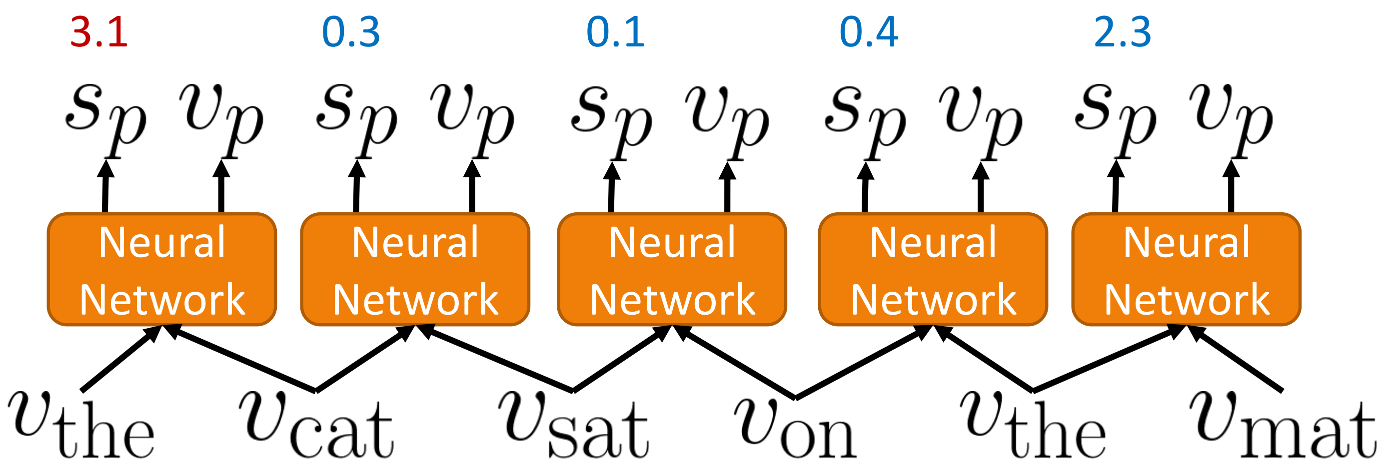
2) score of how plausible the new node would be

$$s_p = U^T v_p$$

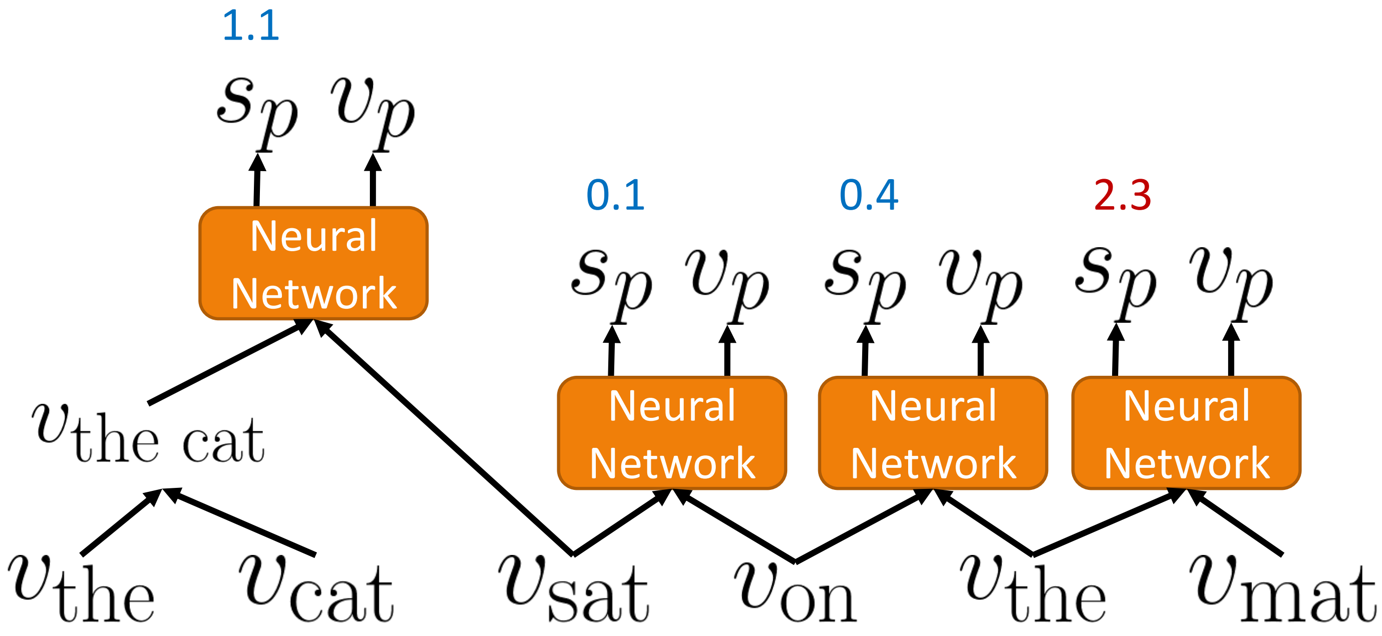


same W parameters at all nodes of the tree
→ weight-tied

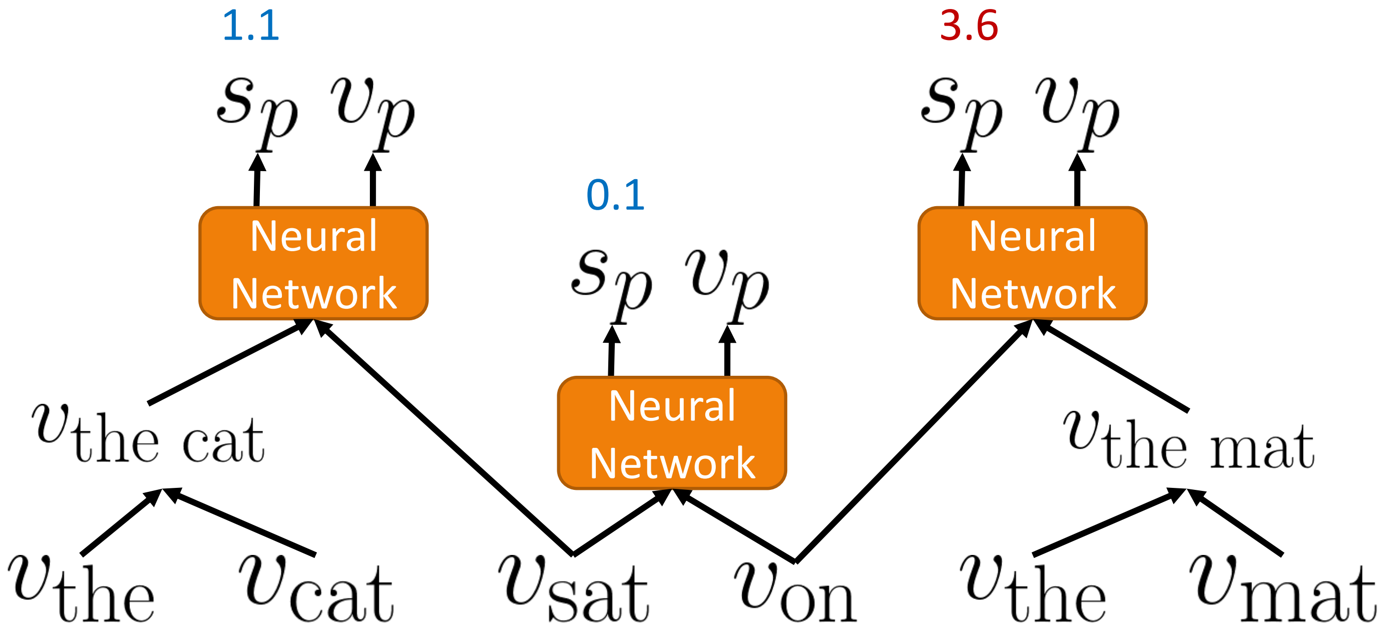
Sentence Parsing via RvNN



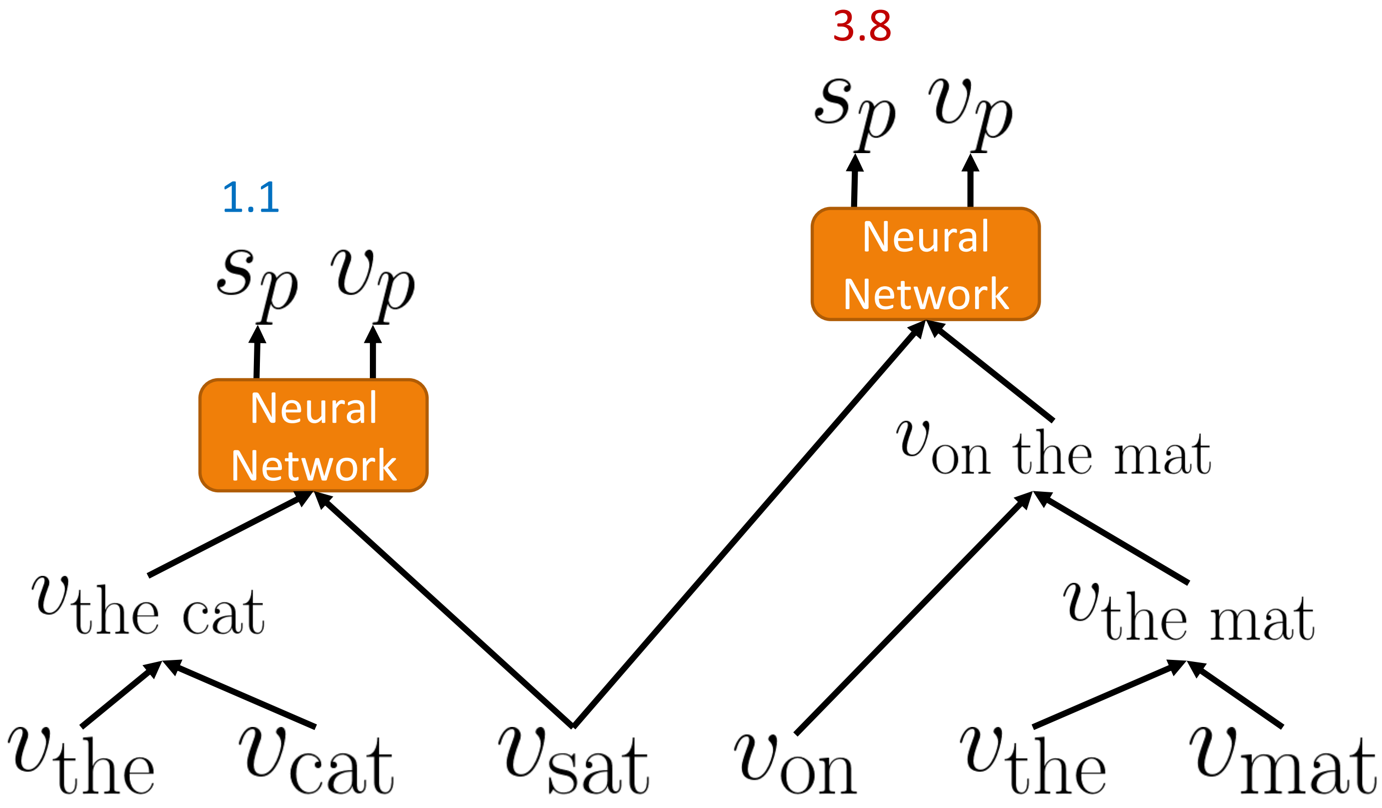
Sentence Parsing via RvNN



Sentence Parsing via RvNN



Sentence Parsing via RvNN



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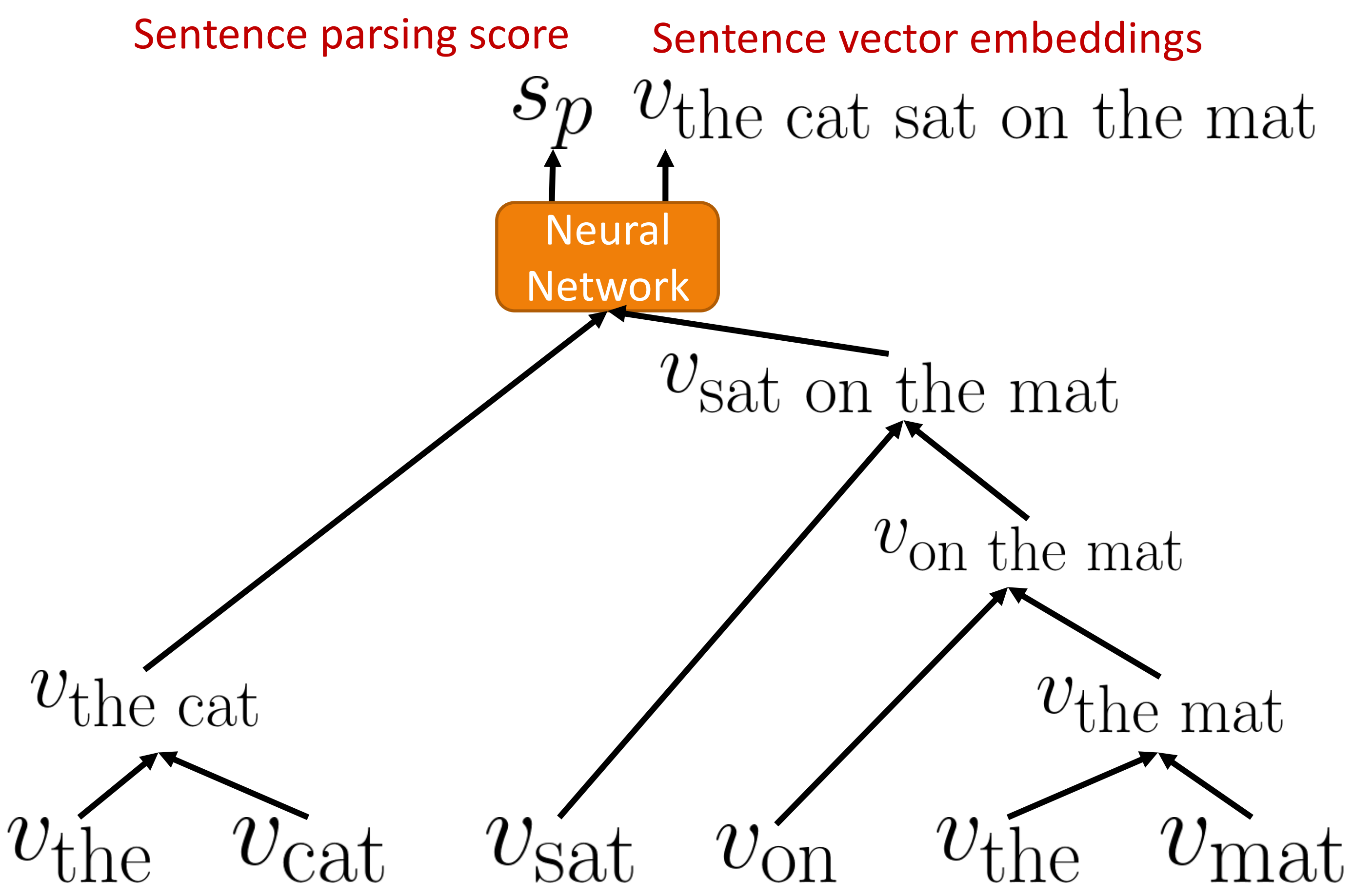


Backpropagation through Structure

Principally the same as general backpropagation (Goller& Küchler, 1996)

$$\frac{\partial C(\theta)}{\partial w_{ij}^{l}} = \frac{\partial C(\theta)}{\partial z_i^{l}} \frac{\partial z_i^{l}}{\partial w_{ij}^{l}}$$

$$\frac{\partial C(\theta)}{\partial z_i^{l}} = \delta_i^{l}$$

$$\frac{\partial z_i^{l}}{\partial w_{ij}^{l}} = \begin{cases} a_j^{l-1} & l > 1 \\ x_j & l = 1 \end{cases}$$

Backward Pass

$$\delta^L = \sigma'(z^L) \odot \nabla C(y)$$
$$\delta^{L-1} = \sigma'(z^{L-1}) \odot (W^L)^T \delta^L$$
$$\vdots$$
$$\delta^l = \sigma'(z^l) \odot (W^{l+1})^T \delta^{l+1}$$
$$\vdots$$

Forward Pass

$$z^1 = W^1 x + b^1 \qquad a^1 = \sigma(z^1)$$
$$\vdots$$
$$z^l = W^l a^{l-1} + b^l \quad a^l = \sigma(z^l)$$
$$\vdots$$

Three differences

① Sum derivatives of W from all nodes
② Split derivatives at each node
③ Add error messages from parent + node itself

1) Sum derivatives of W from all nodes

$$\frac{\partial}{\partial W} f(W(f(Wx))$$

$$= f'(W(f(Wx)) \left(\left(\frac{\partial}{\partial W} W \right) f(Wx) + W \frac{\partial}{\partial W} f(Wx) \right)$$

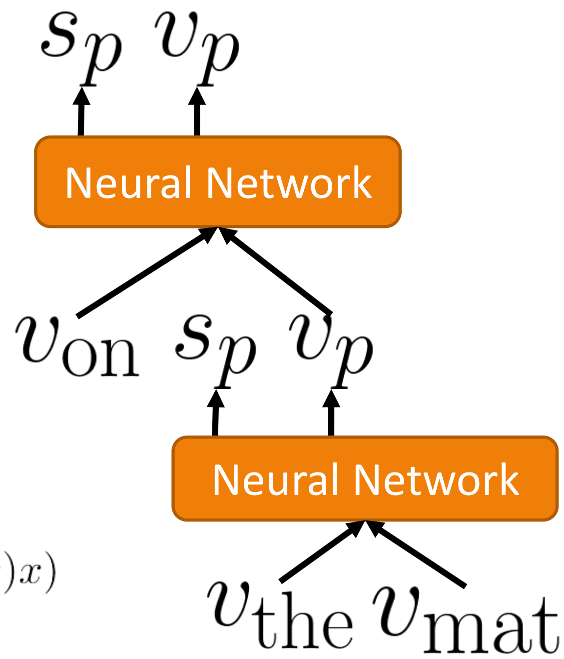
$$= f'(W(f(Wx)) \left(f(Wx) + W f'(Wx) x \right)$$

$$\frac{\partial}{\partial W_2} f(W_2(f(W_1x)) + \frac{\partial}{\partial W_1} f(W_2(f(W_1x))$$

$$= f'(W_2(f(W_1x)) \left(f(W_1x) \right) + f'(W_2(f(W_1x)) \left(W_2 f'(W_1x) x \right)$$

$$= f'(W_2(f(W_1x)) \left(f(W_1x) + W_2 f'(W_1x) x \right)$$

$$= f'(W(f(Wx)) \left(f(Wx) + W f'(Wx) x \right)$$

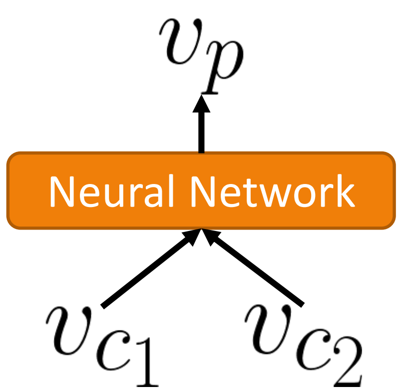


$$v_p = \sigma(W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$

2) Split derivatives at each node

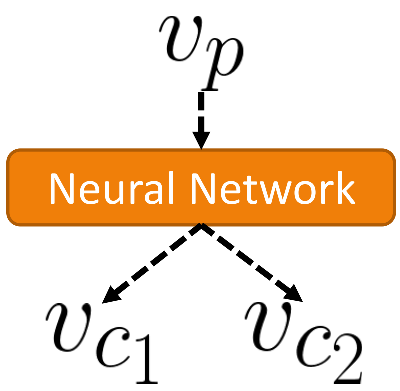
During forward propagation, the parent node is computed based on two children

$$v_p = \sigma(W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$



During backward propagation, the errors should be computed wrt each of them

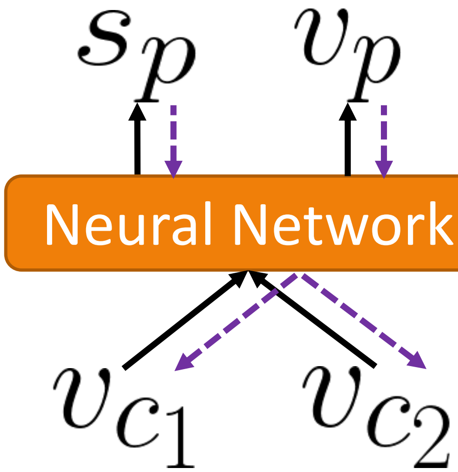
$$\delta_{p \to c_1 c_2} = [\delta_{p \to c_1} \delta_{p \to c_2}]$$



3) Add error messages

For each node, the error message is compose of

- Error propagated from parent
- Error from the current node



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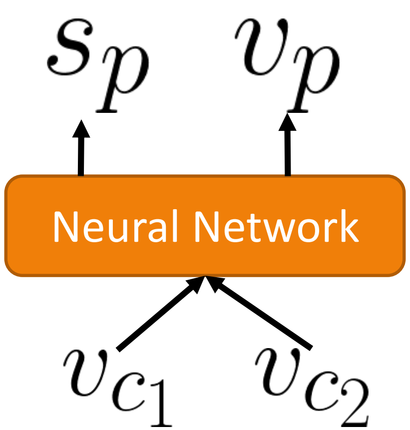
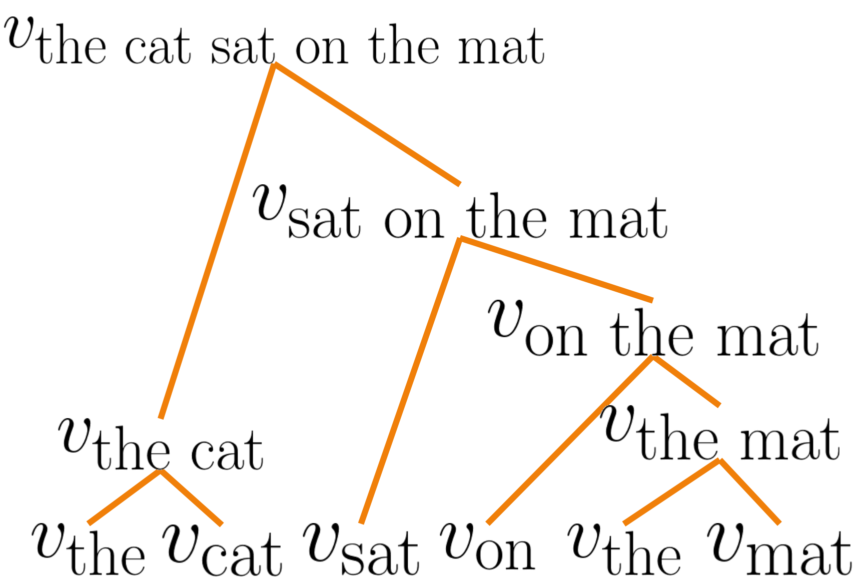
Composition Matrix *W*



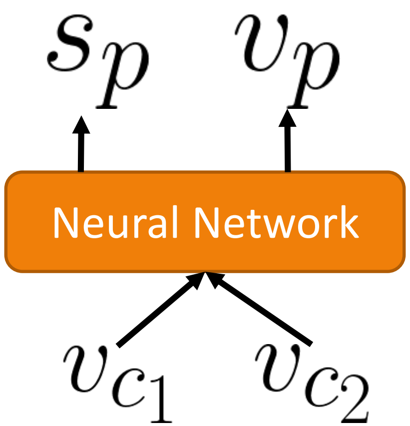
$$v_p = \sigma(W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$

$$s_p = U^T v_p$$



Issue: using the same network *W* for different compositions

Syntactically Untied RvNN

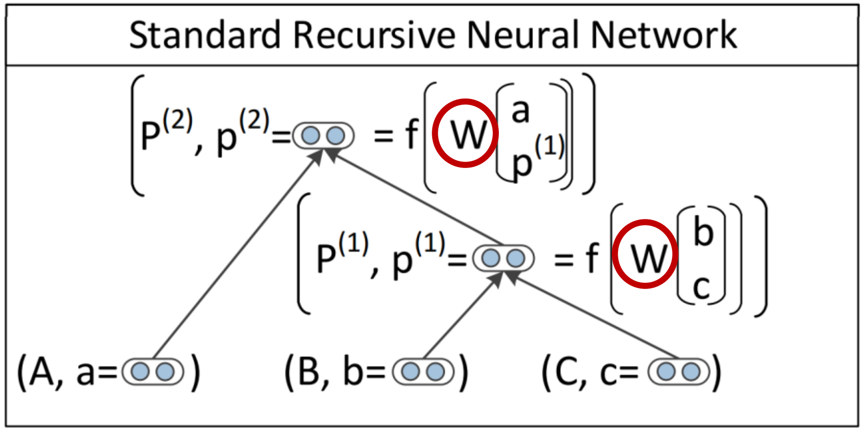


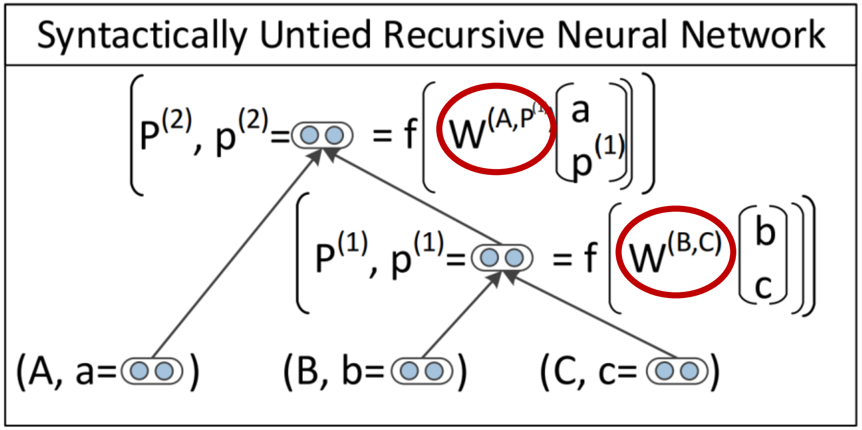
Idea: the composition function is conditioned on the syntactic categories

Benefit

- Composition function are syntax-dependent
- Allows different composition functions for word pairs, e.g. Adv + AdjP, VP + NP

Issue: speed due to many candidates





Compositional Vector Grammar

Compute score only for a subset of trees coming from a simpler, faster model (Socher et al, 2013)

- Prunes very unlikely candidates for speed
- Provides coarse syntactic categories of the children for each beam candidate

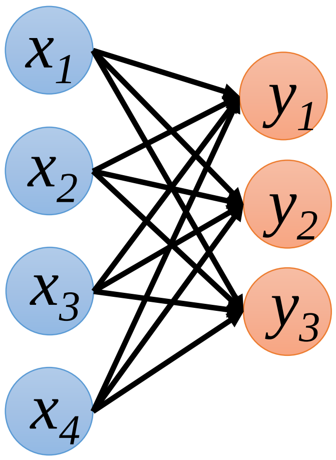
Probability context-free grammar (PCFG) helps decrease the search space

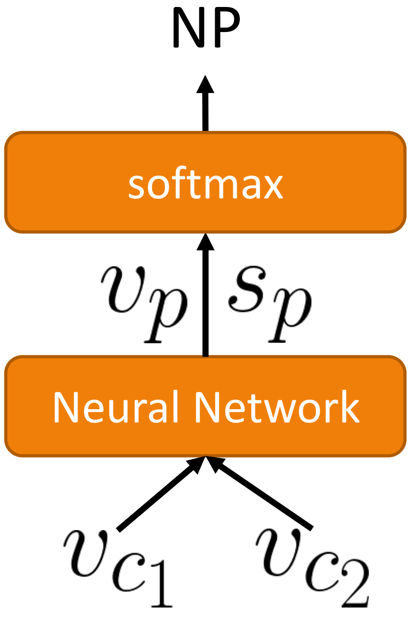
Labels for RvNN

The score can be passed through a softmax function to compute the probability of each category

$$p(\text{class} \mid v_p) = \text{softmax}(s_p)$$

$$\text{softmax}(f)_i = \frac{\exp(f_i)}{\sum_j \exp(f_j)}$$





Softmax loss → cross-entropy error for optimization

Socher et al., "Parsing Natural Scenes and Natural Language with Recursive Neural Networks," in ICML, 2011.

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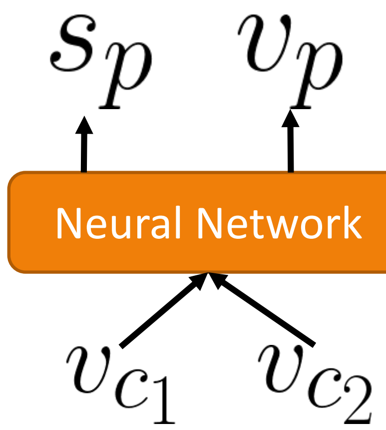
Recursive Neural Network

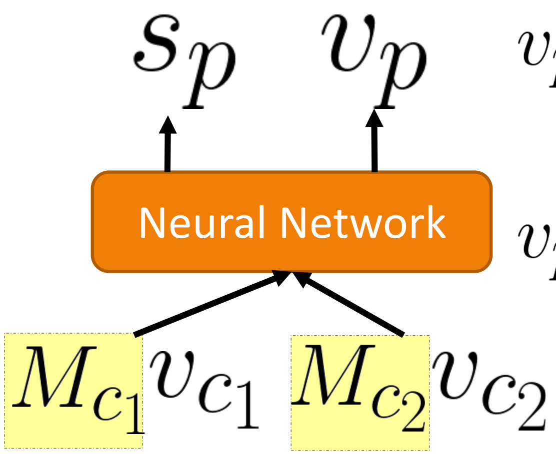


$$v_p = \sigma(W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$

$$s_p = U^T v_p$$

Issue: some words act mostly as an operator, e.g. “very” in “very good”

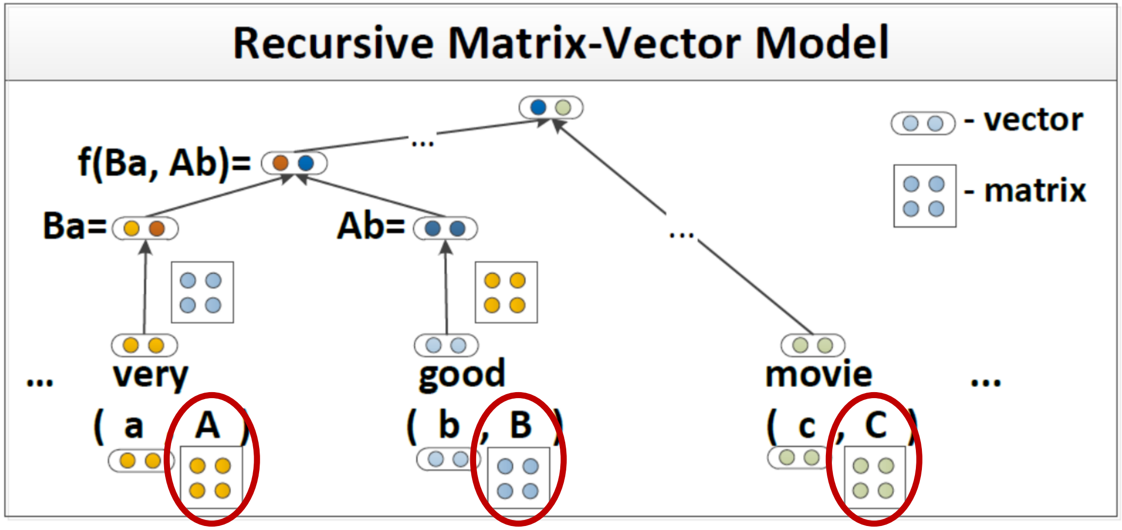
Matrix-Vector Recursive Neural Network



$$v_p = \sigma(W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$

$$v_p = \sigma(W \begin{bmatrix} M_{c_2}v_{c_1} \\ M_{c_1}v_{c_2} \end{bmatrix} + b)$$

Idea: each word can additionally serve as an operator



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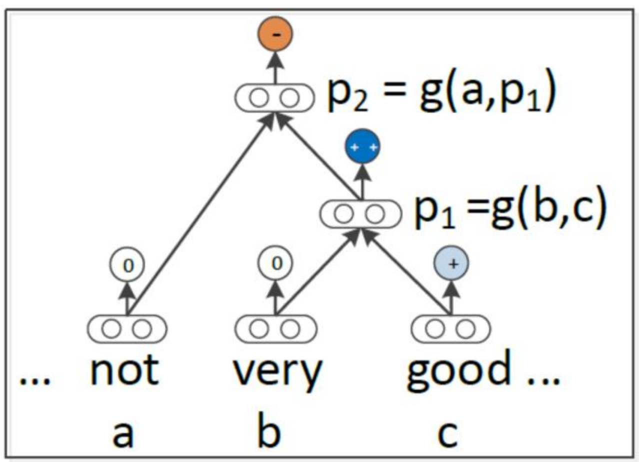
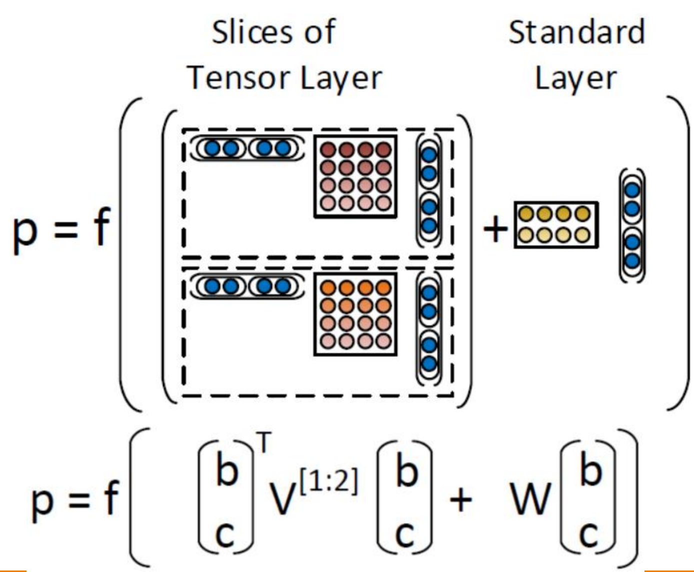
Recursive Neural Tensor Network

$$v_p = \sigma(W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$

Idea: allow more interactions of vectors

$$v_p = \sigma(\begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix}^T V_{c_1,c_2} \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + W \begin{bmatrix} v_{c_1} \\ v_{c_2} \end{bmatrix} + b)$$





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Language Compositionality

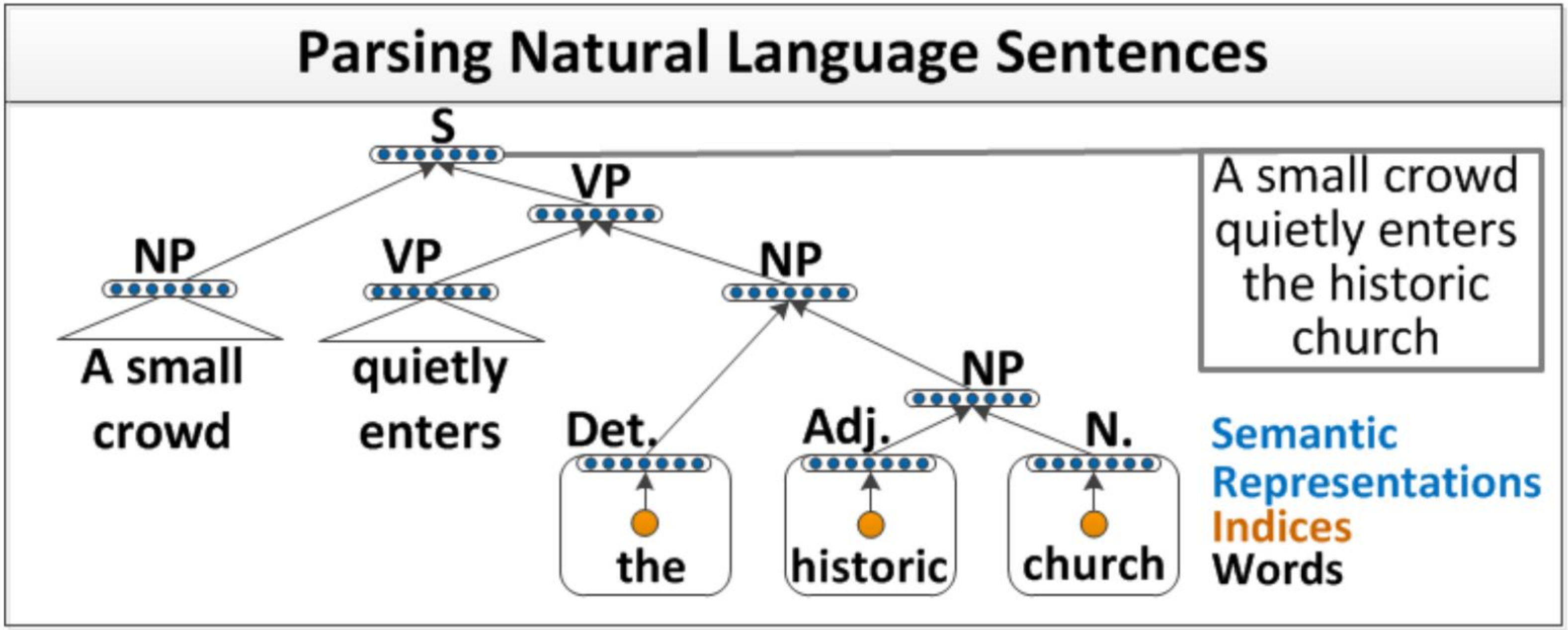
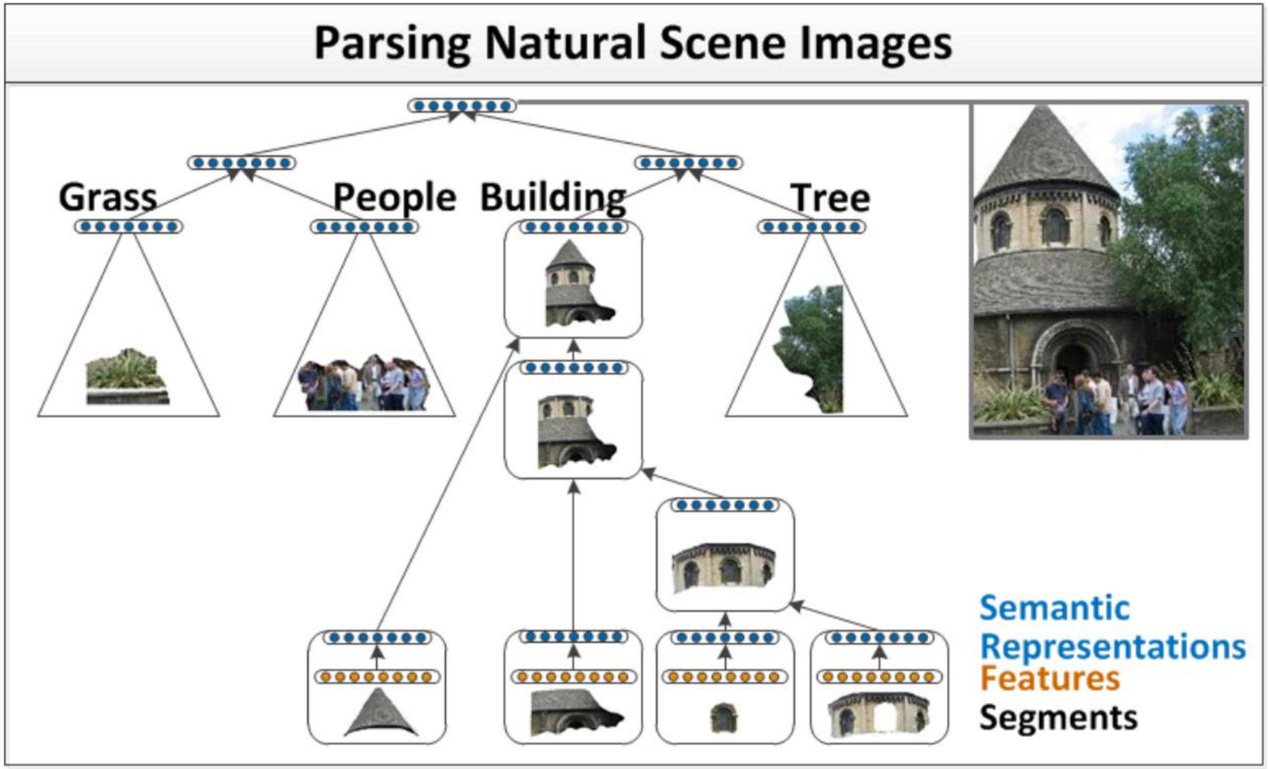


Image Compositionality

Idea: image can be composed by the visual segments (same as natural language parsing)



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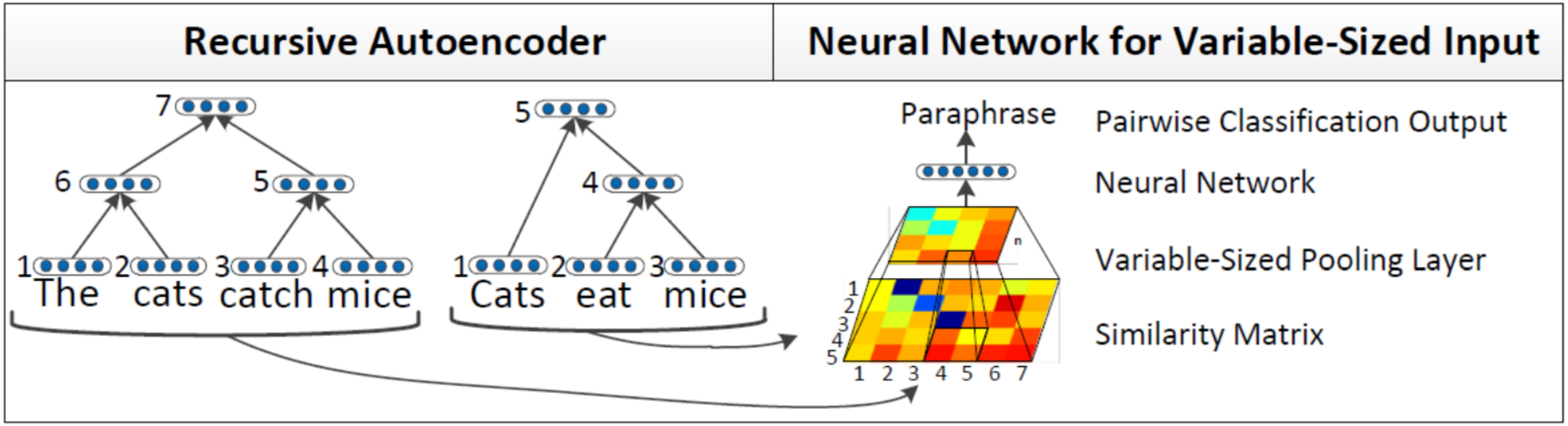
Paraphrase for Learning Sentence Vectors

A pair-wise sentence comparison of nodes in parsed trees for learning sentence embeddings



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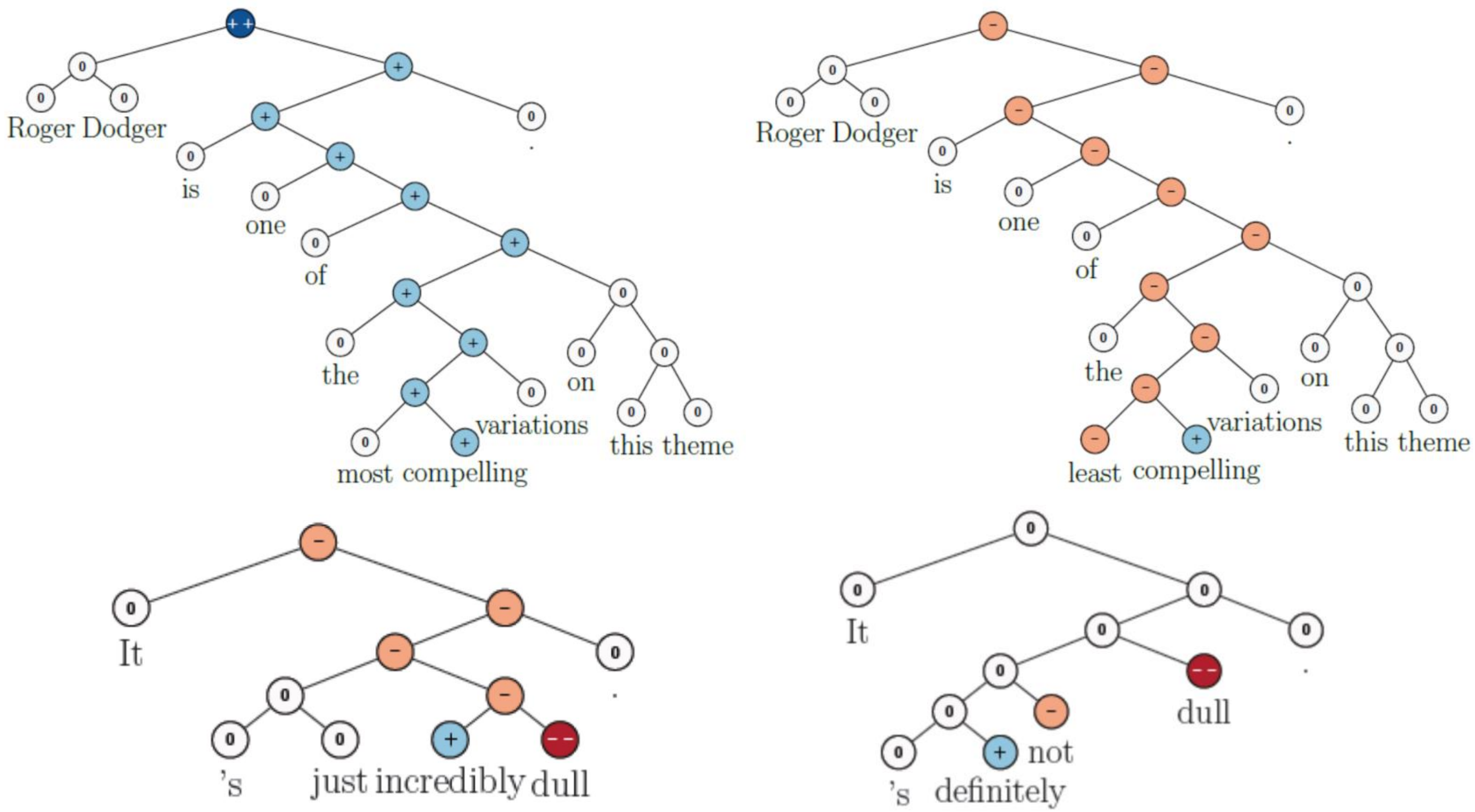
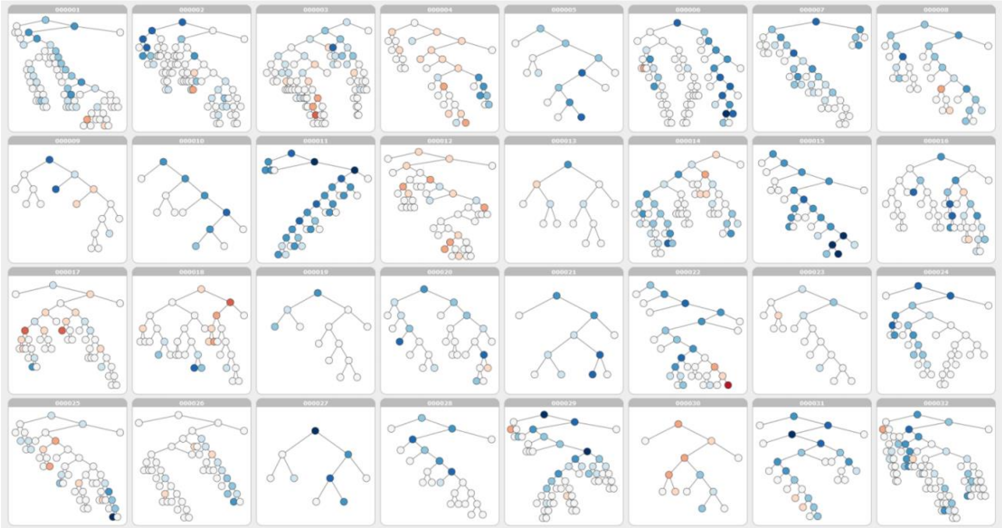
Sentiment Analysis

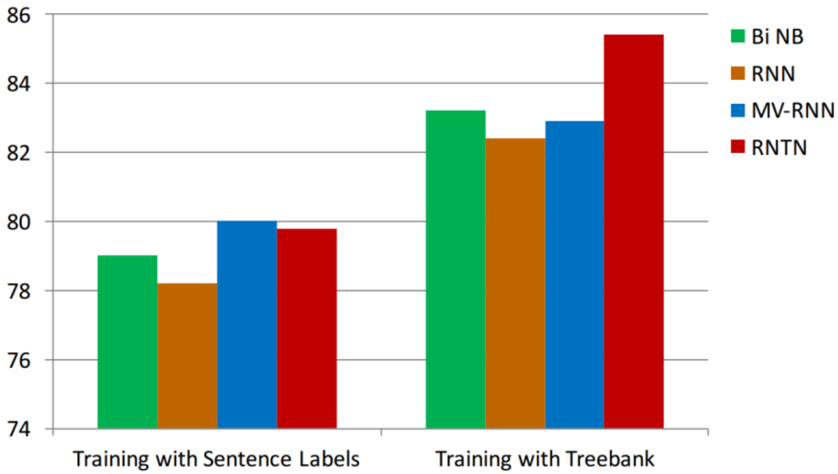


Sentiment analysis for sentences with negation words can benefit from RvNN

Sentiment Analysis

Sentiment Treebank with richer annotations

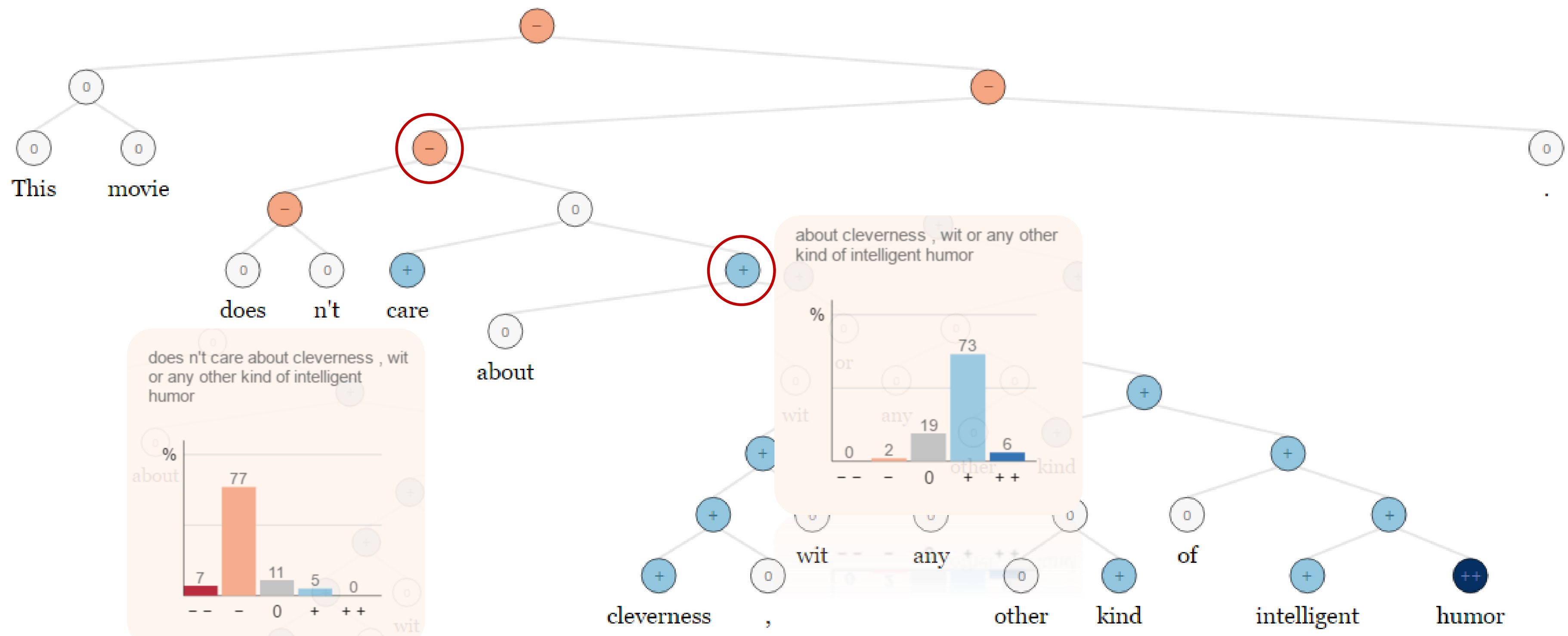




Phrase-level sentiment labels indeed improve the performance

Sentiment Tree Illustration

Stanford live demo: http://nlp.stanford.edu/sentiment/



Phrase-level annotations learn the specific compositional functions for sentiment

Concluding Remarks

Recursive Neural Network

- Idea: syntactic compositionality & language recursion

Network Variants

- Standard Recursive Neural Network
  - Weight-Tied
  - Weight-Untied
- Matrix-Vector Recursive Neural Network
- Recursive Neural Tensor Network