Applied Deep Learning

Sequence Modeling

Language Modeling & Recurrent Neural Networks

September 11th, 2024 http://adl.miulab.tw

National Taiwan University
國立臺灣大學

Outline

- Meaning Representations
  - Knowledge-Based Representation
  - Corpus-Based Representation
- Language Modeling
  - N-gram Language Model
  - Feed-Forward Neural Language Model
  - Recurrent Neural Network Language Model (RNNLM)
- Recurrent Neural Network
  - Definition
  - Training via Backpropagation through Time (BPTT)
  - Training Issue
  - Extension
- RNN Applications
  - Sequential Input
  - Sequential Output
    - Aligned Sequential Pairs (Tagging)
    - Unaligned Sequential Pairs (Seq2Seq/Encoder-Decoder)

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Meaning Representations in Computers

How to represent words in computers?

Knowledge-Based Representation

Corpus-Based Representation

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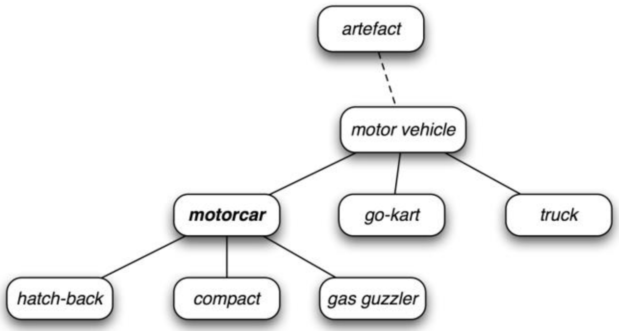
Knowledge-Based Representation

- Hypernyms (is-a) relationships of WordNet

```
from nltk.corpus import wordnet as wn
panda = wn.synset('panda.n.01')
hyper = lambda s: s.hypernyms()
list(panda.closure(hyper))
```

```
[Synset('procyonid.n.01'),
Synset('carnivore.n.01'),
Synset('placental.n.01'),
Synset('mammal.n.01'),
Synset('vertebrate.n.01'),
Synset('chordate.n.01'),
Synset('animal.n.01'),
Synset('organism.n.01'),
Synset('living_thing.n.01'),
Synset('whole.n.02'),
Synset('object.n.01'),
Synset('physical_entity.n.01'),
Synset('entity.n.01')]
```



Issues:
- newly-invented words
- subjective
- annotation effort
- difficult to compute word similarity

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Corpus-Based Representation

- Atomic symbols: ***one-hot*** representation

car $[0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ \ldots\ 0]$

car

Issues: difficult to compute the similarity (i.e. comparing “car” and “motorcycle”)

$[0\ 0\ 0\ 0\ 0\ 0\ 1\ 0\ 0\ \ldots\ 0]$ AND $[0\ 0\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ \ldots\ 0] = 0$

car motorcycle

Idea: words with similar meanings often have similar neighbors

Corpus-Based Representation

- Neighbor-based representation
  - Co-occurrence matrix constructed via neighbors
  - Neighbor definition: full document vs. windows

full document

word-document co-occurrence matrix gives general topics
→ “Latent Semantic Analysis”

windows

context window for each word
→ capture syntactic (e.g. POS) and semantic information

Window-Based Co-occurrence Matrix

- Example
  - Window length=1
  - Left or right context
  - Corpus:

I love AI.
I love deep learning.
I enjoy learning.

similarity > 0

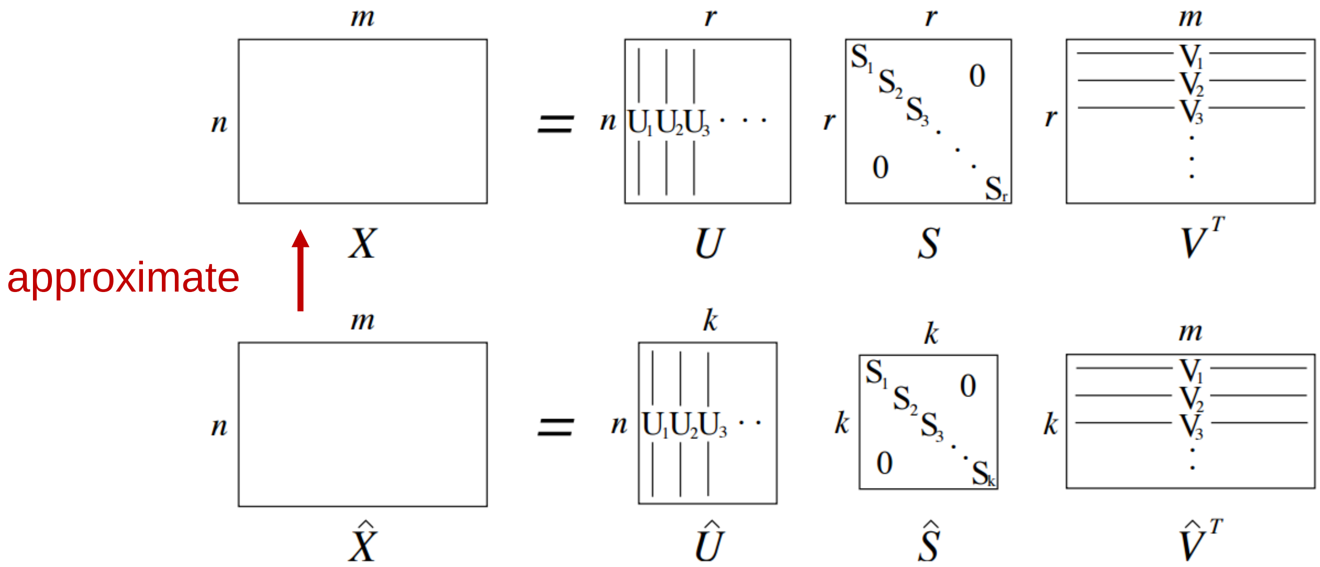
Counts	I	love	enjoy	AI	deep	learning
I	0	2	1	0	0	0
love	2	0	0	1	1	0
enjoy	1	0	0	0	0	1
AI	0	1	0	0	0	0
deep	0	1	0	0	0	1
learning	0	0	1	0	1	0

Issues:
- matrix size increases with vocabulary
- high dimensional
- sparsity → poor robustness

Idea: low dimensional word vector

Low-Dimensional Dense Word Vector

- Method 1: dimension reduction on the matrix
- Singular Value Decomposition (SVD) of co-occurrence matrix X



Low-Dimensional Dense Word Vector

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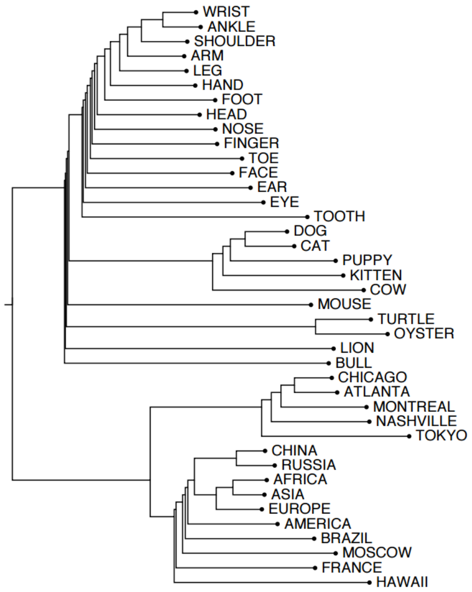
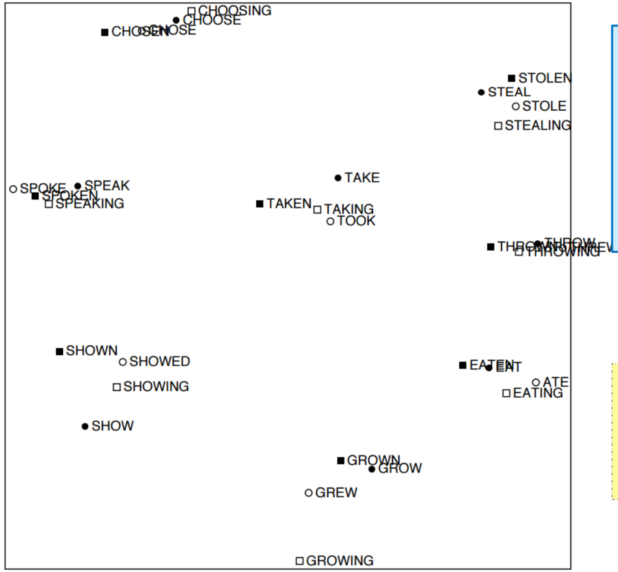


semantic relations



syntactic relations

Issues:

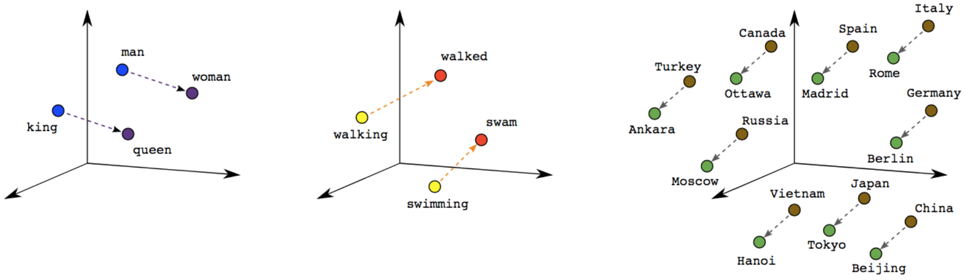
- computationally expensive: $O(mn^2)$ when n<m for nxm matrix
- difficult to add new words

Idea: directly learn low-dimensional word vectors

Rohde et al., "An Improved Model of Semantic Similarity Based on Lexical Co-Occurrence," 2005.

Low-Dimensional Dense Word Vector

- Method 2: directly learn low-dimensional word vectors
  - Learning representations by back-propagation. (Rumelhart et al., 1986)
  - A neural probabilistic language model (Bengio et al., 2003)
  - NLP (almost) from Scratch (Collobert & Weston, 2008)
  - Recent and most popular models: word2vec (Mikolov et al. 2013) and Glove (Pennington et al., 2014)
    - As known as “Word Embeddings”



Male-Female Verb Tense Country-Capital

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Language Modeling
語言模型

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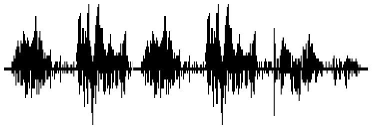
Language Modeling

- Goal: estimate the probability of a word sequence

$$P(w_1, \cdots, w_m)$$

- Example task: determinate whether a sequence is grammatical or makes more sense



recognize speech
or
wreck a nice beach

If P(recognize speech)
> P(wreck a nice beach)

Output = "recognize speech"

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N-Gram Language Modeling

- Goal: estimate the probability of a word sequence

$$P(w_1, \cdots, w_m)$$

- N-gram language model
  - Probability is conditioned on a window of (*n*-1) previous words

$$P(w_1, \cdots, w_m) = \prod_{i=1}^{m} P(w_i \mid w_1, \cdots, w_{i-1}) \approx \prod_{i=1}^{m} P(w_i \mid w_{i-(n-1)}, \cdots, w_{i-1})$$

  - Estimate the probability based on the training data

$$P(\text{beach}|\text{nice}) = \frac{C(\text{nice each})}{C(\text{nice})}$$

Count of “nice beach” in the training data

Count of “nice” in the training data

Issue: some sequences may not appear in the training data

N-Gram Language Modeling

- Training data:
  - The dog ran ……
  - The cat jumped ……

$$P(\text{ jumped} \mid \text{dog }) = \cancel{0}\ \ 0.0001$$

$$P(\text{ ran} \mid \text{cat }) = \cancel{0}\ \ 0.0001$$

give some small probability
→ smoothing

- The probability is not accurate
- Reason: impossible to collect all possible texts as training data

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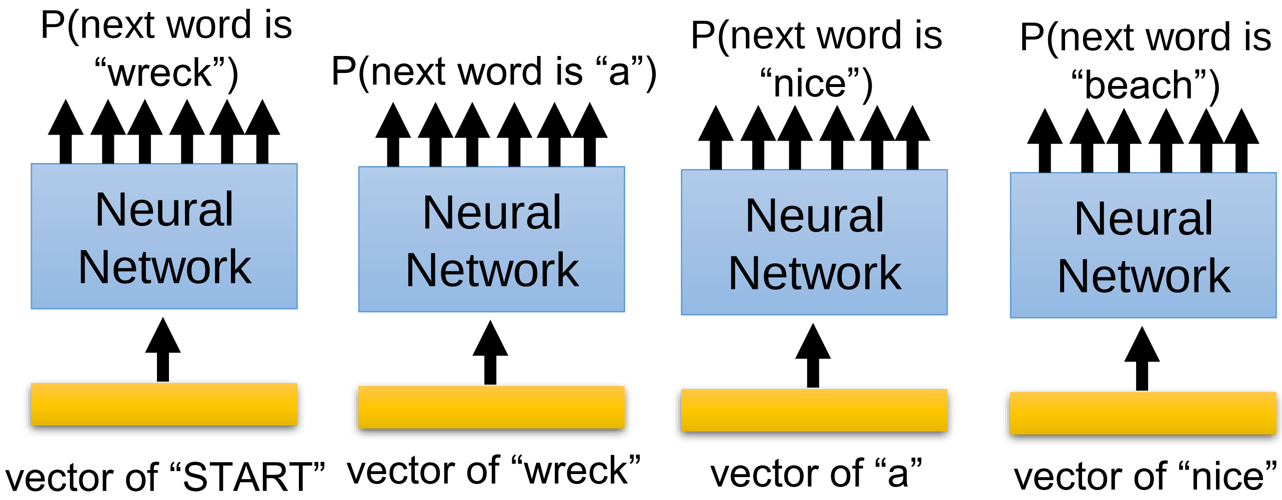
Neural Language Modeling

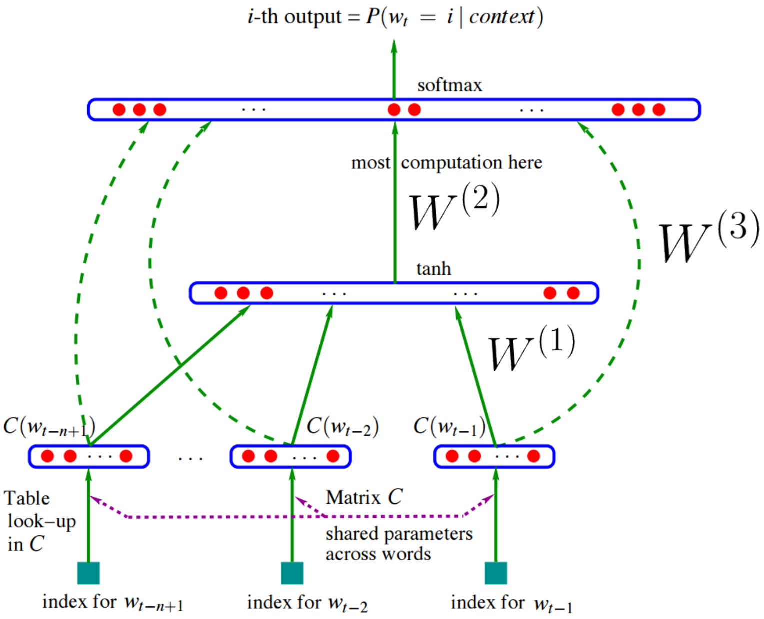
- Idea: estimate $P(w_i \mid w_{i-(n-1)}, \cdots, w_{i-1})$ not from count, but from NN prediction

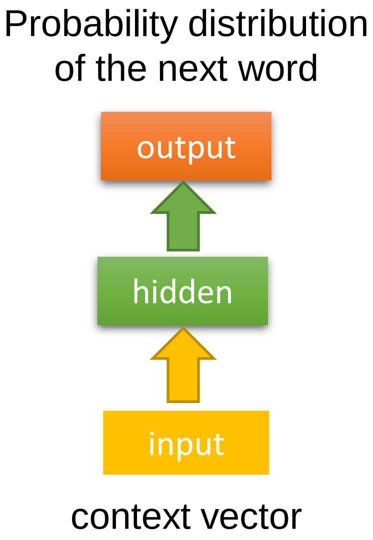
P("wreck a nice beach") = P(wreck | START) P(a | wreck) P(nice | a) P(beach | nice)



Neural Language Modeling

$$\hat{y} = \text{softmax}(W^{(2)}\sigma(W^{(1)}x + b^{(1)}) + W^{(3)}x + b^{(3)})$$

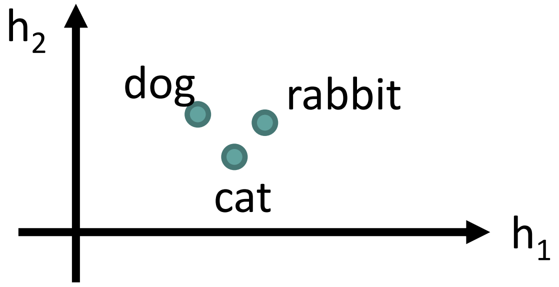




Bengio et al., "A Neural Probabilistic Language Model," in *JMLR*, 2003.

Neural Language Modeling

- The input layer (or hidden layer) of the related words are close



  - If P(jump | cat) is large, P(jump | dog) increases accordingly (even there is not "… dog jumps …" in the data)

Smoothing is automatically done

Issue: fixed context window for conditioning

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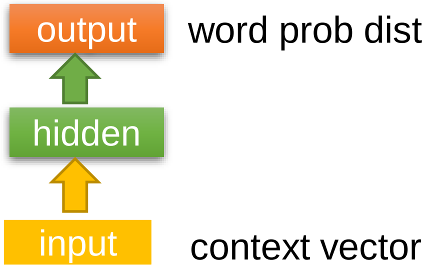
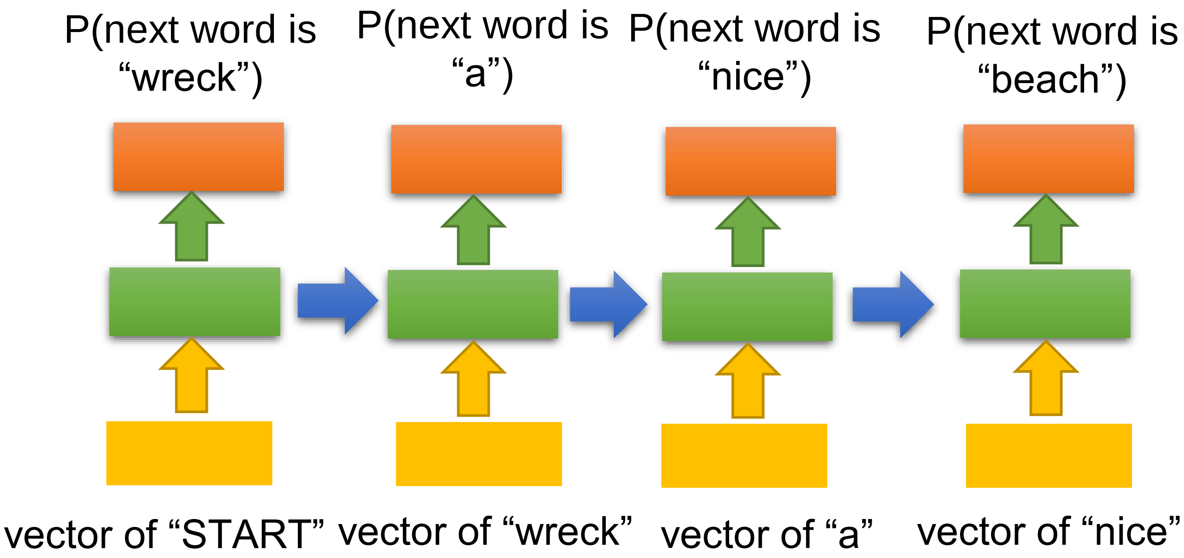
Recurrent Neural Network

- Idea: condition the neural network on all previous words and tie the weights at each time step
- Assumption: temporal information matters

RNN Language Modeling





Idea: pass the information from the previous hidden layer to leverage all contexts

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Recurrent Neural Network

詳細解析鼎鼎大名的RNN

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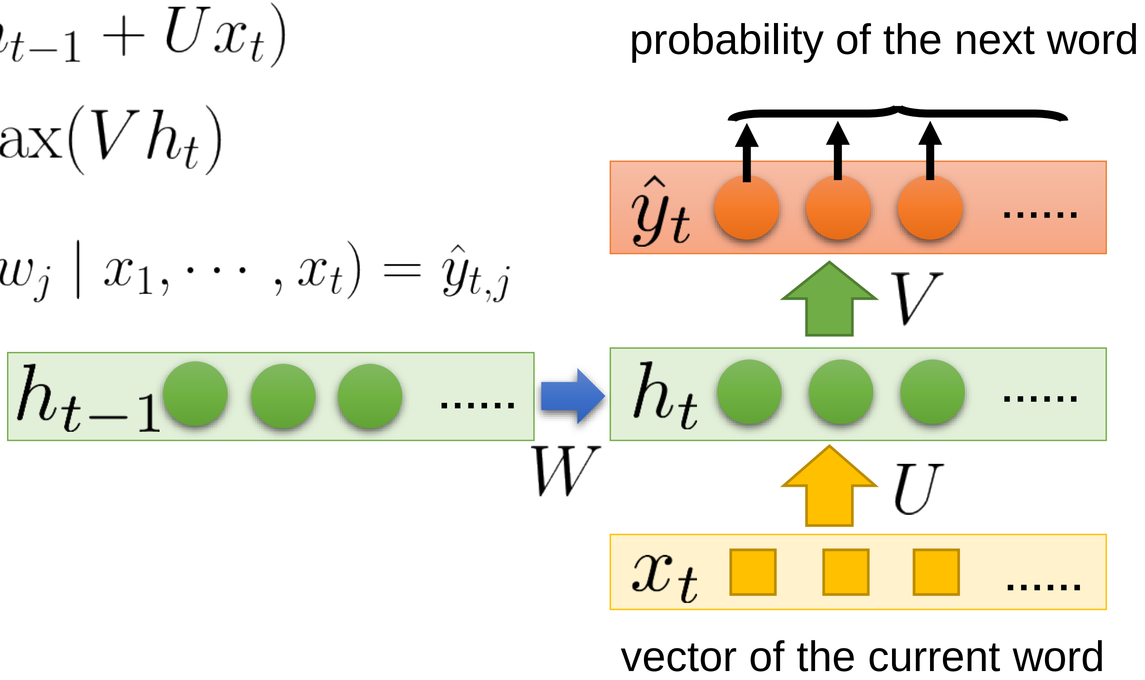
RNNLM Formulation

- At each time step,

$$h_t = \sigma(W h_{t-1} + U x_t)$$

$$\hat{y}_t = \mathrm{softmax}(V h_t)$$

$$P(x_{t+1} = w_j \mid x_1, \cdots, x_t) = \hat{y}_{t,j}$$



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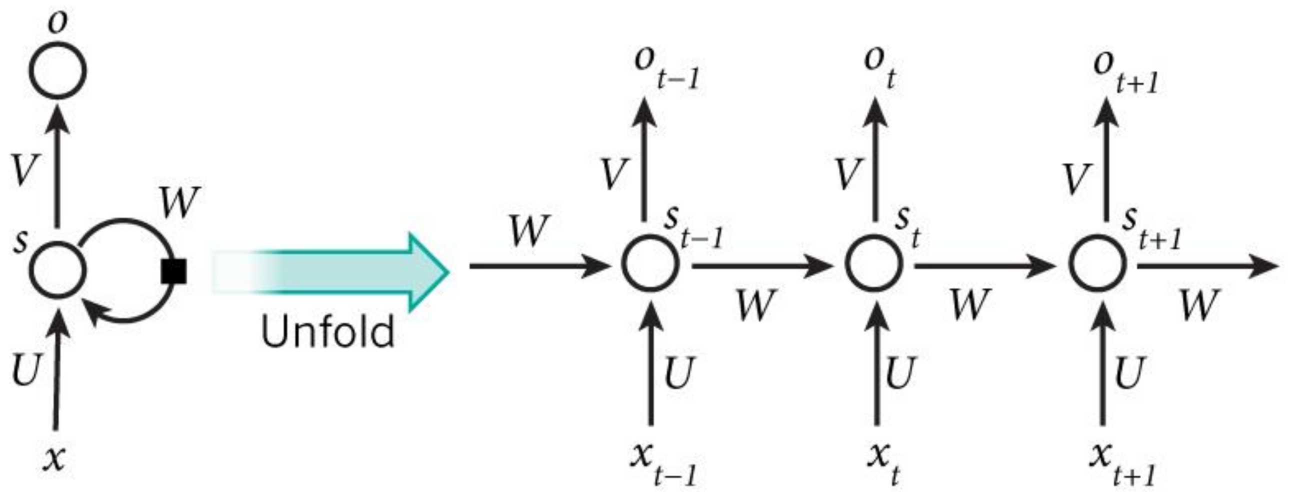
Recurrent Neural Network Definition

$$s_t = \sigma(W s_{t-1} + U x_t)$$
$$o_t = \mathrm{softmax}(V s_t)$$

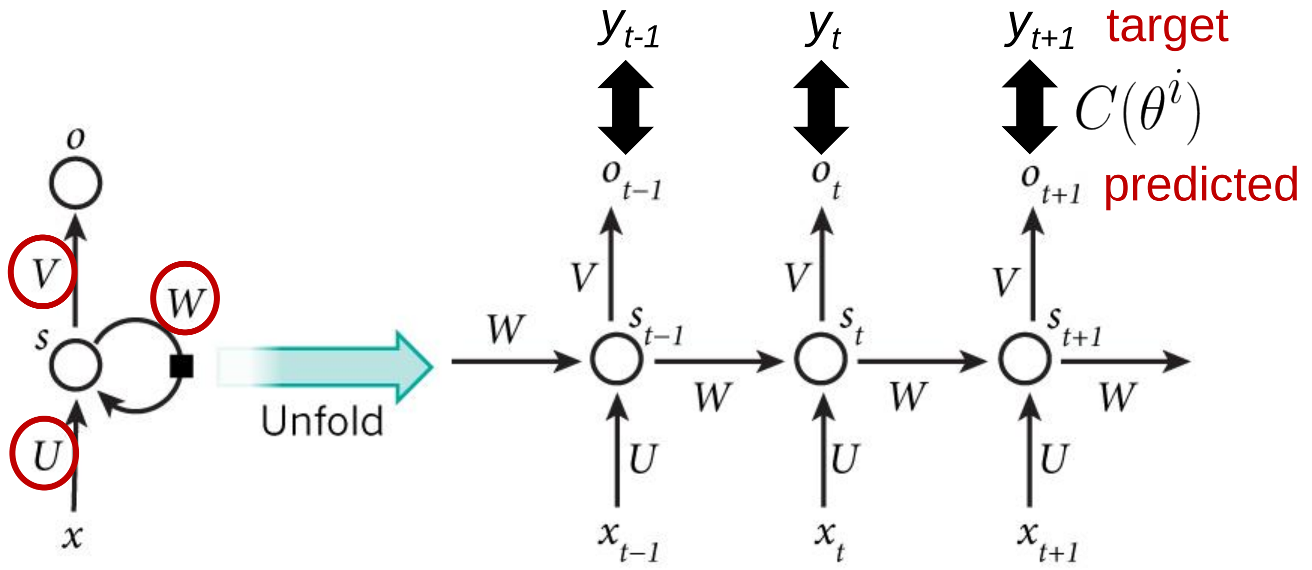
$\sigma(\cdot)$: tanh, ReLU



Model Training

- All model parameters $\theta = \{U, V, W\}$ can be updated by

$$\theta^{i+1} \leftarrow \theta^{i} - \eta \nabla_{\theta} C(\theta^{i})$$



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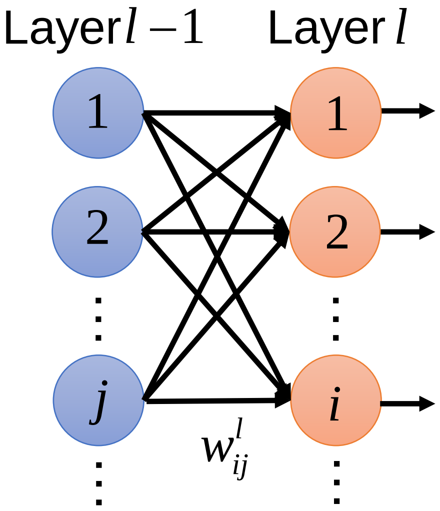
Backpropagation

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



$\boxed{\delta_i^l}$ Error signal

$$\begin{cases} a_j^{l-1} & l > 1 \\ x_j & l = 1 \end{cases}$$

Backward Pass

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

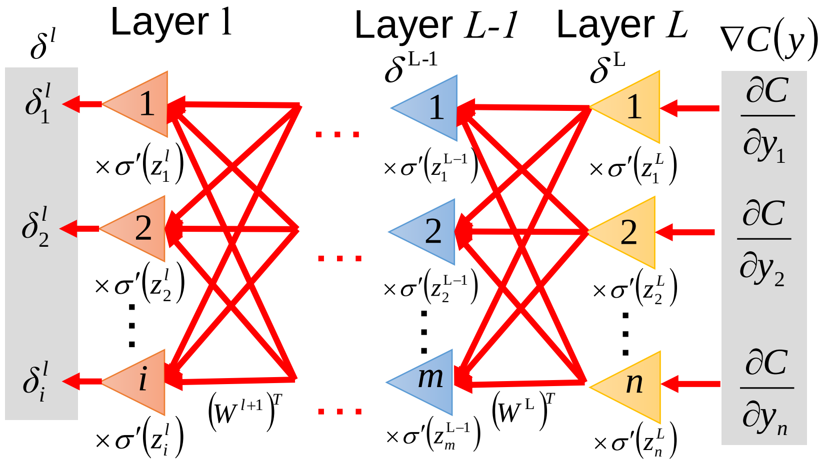
Forward Pass

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

Backpropagation

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

$\boxed{\delta_i^l}$ Error signal



Backward Pass

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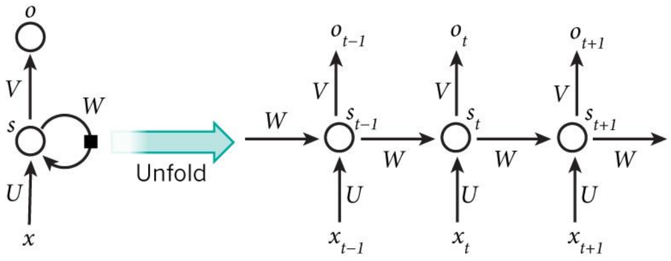
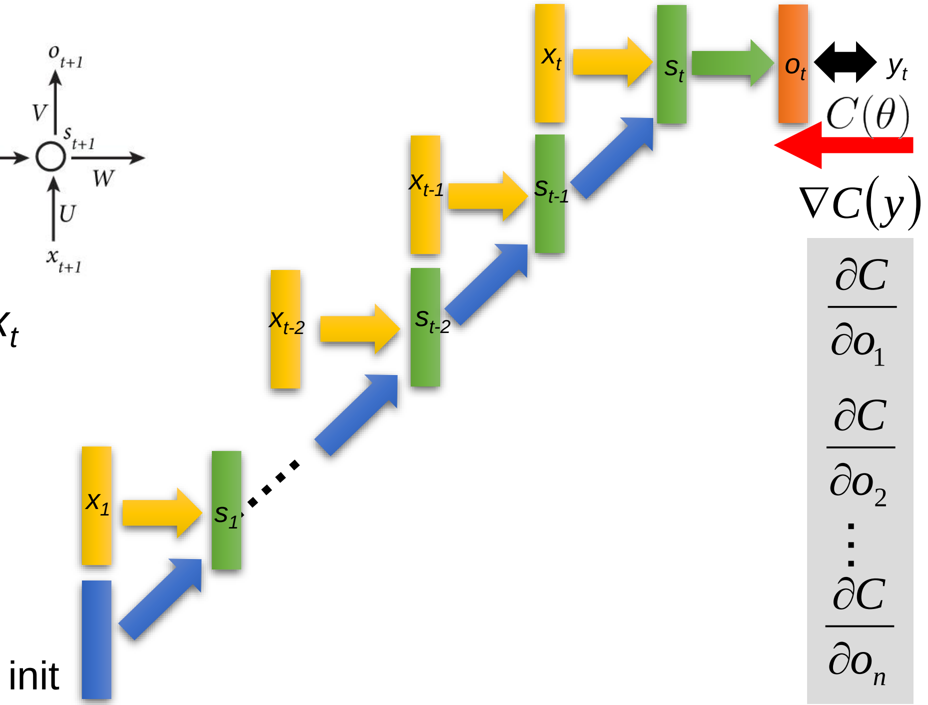
$$\vdots$$
$$\delta^l = \sigma'(z^l) \odot (W^{l+1})^T \delta^{l+1}$$
$$\vdots$$

Backpropagation through Time (BPTT)

- <u>Unfold</u>

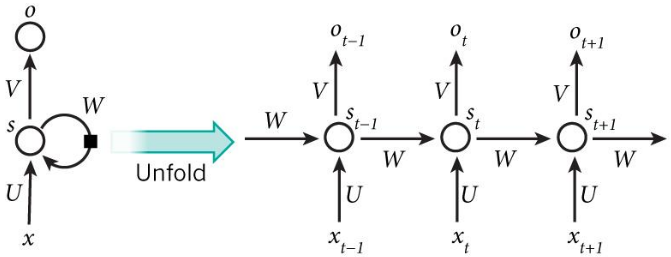


  - Input: init, x_1, x_2, …, x_t
  - Output: o_t
  - Target: y_t



Backpropagation through Time (BPTT)

- Unfold



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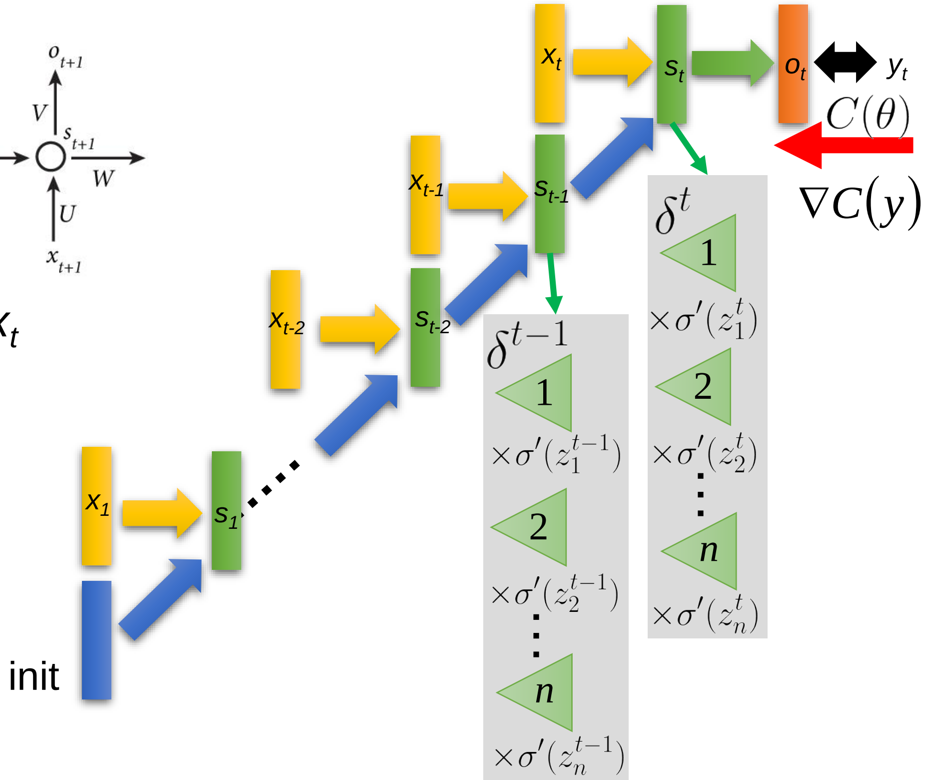

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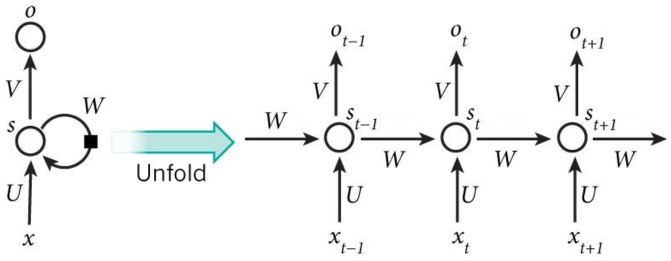

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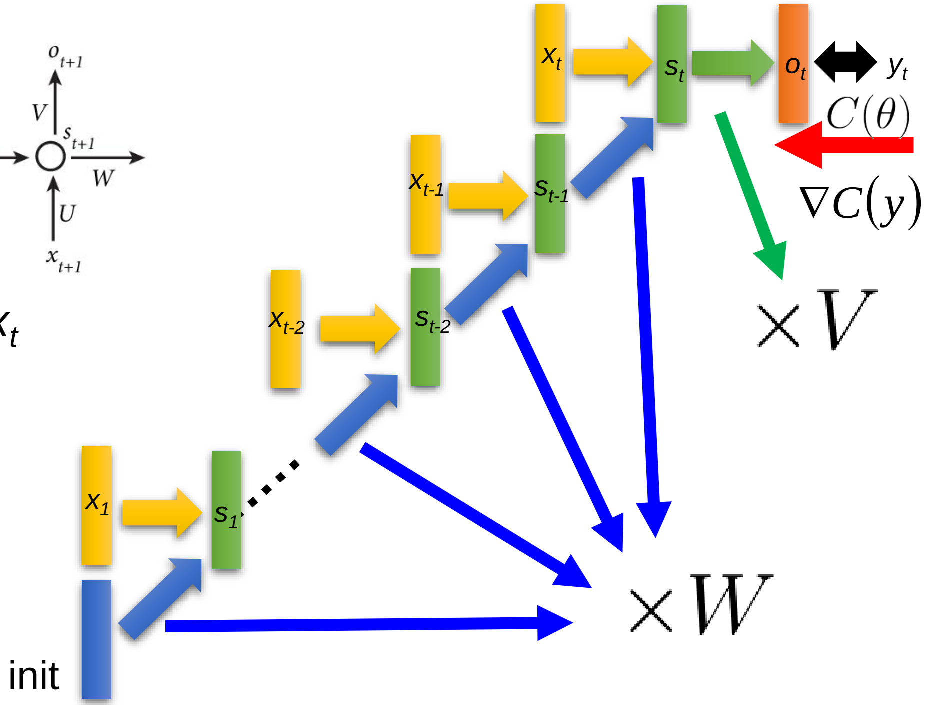

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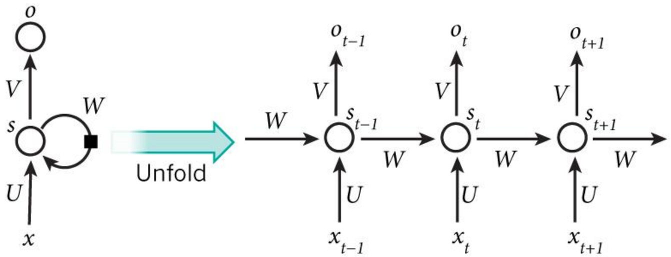

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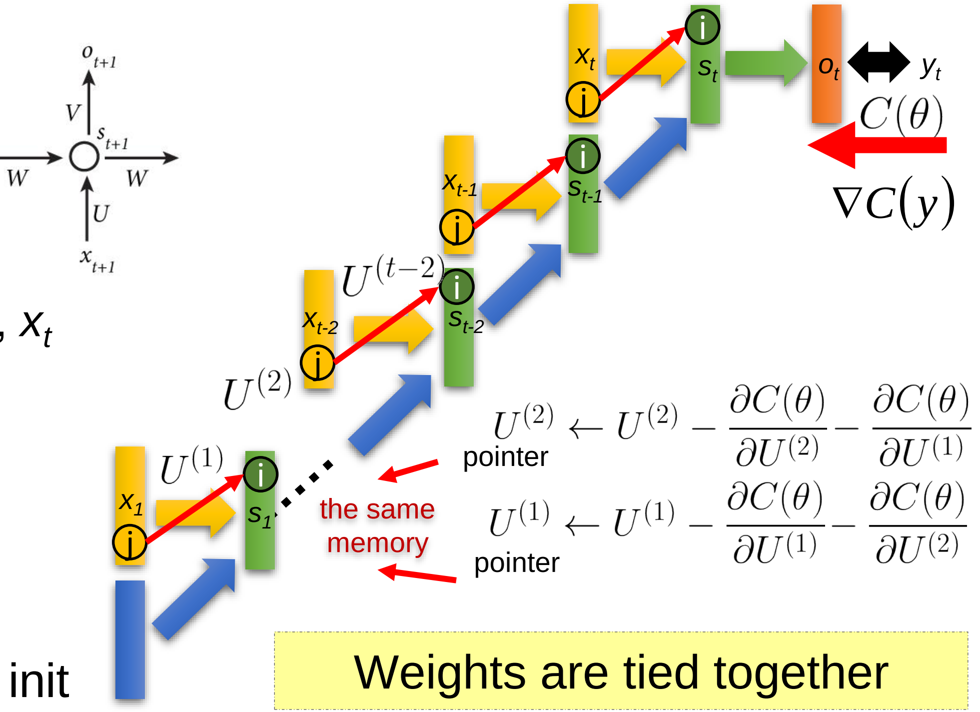


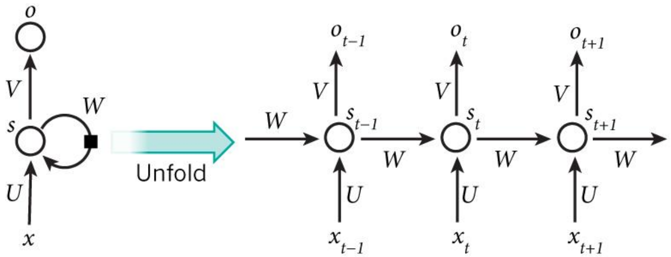
$$U^{(2)} \leftarrow U^{(2)} - \frac{\partial C(\theta)}{\partial U^{(2)}} - \frac{\partial C(\theta)}{\partial U^{(1)}}$$

$$U^{(1)} \leftarrow U^{(1)} - \frac{\partial C(\theta)}{\partial U^{(1)}} - \frac{\partial C(\theta)}{\partial U^{(2)}}$$

Weights are tied together

Backpropagation through Time (BPTT)

- Unfold



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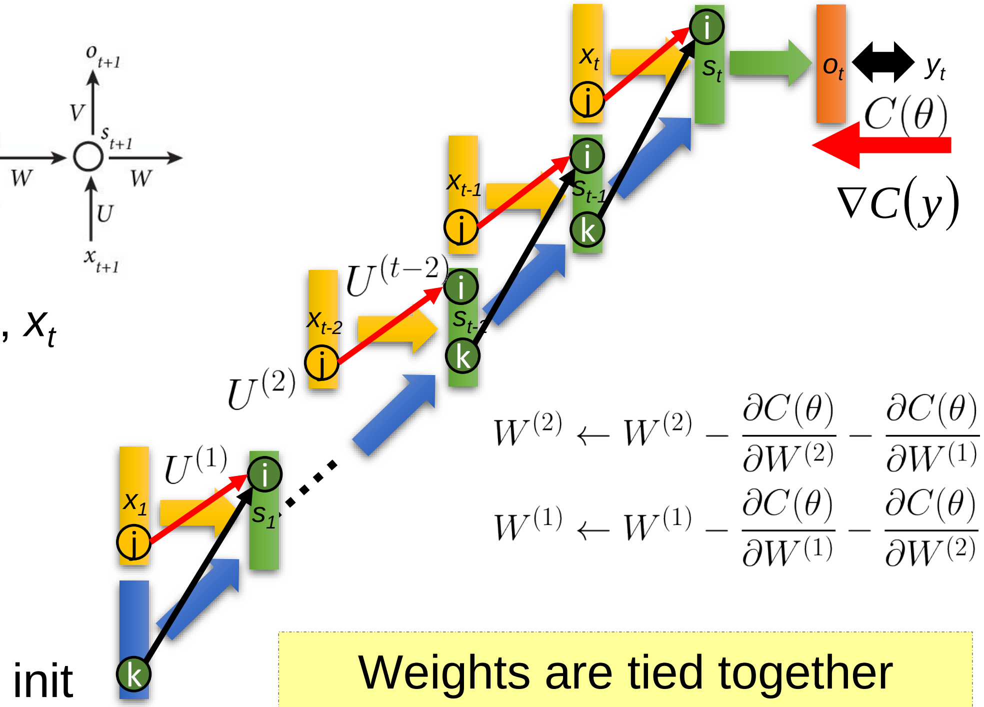

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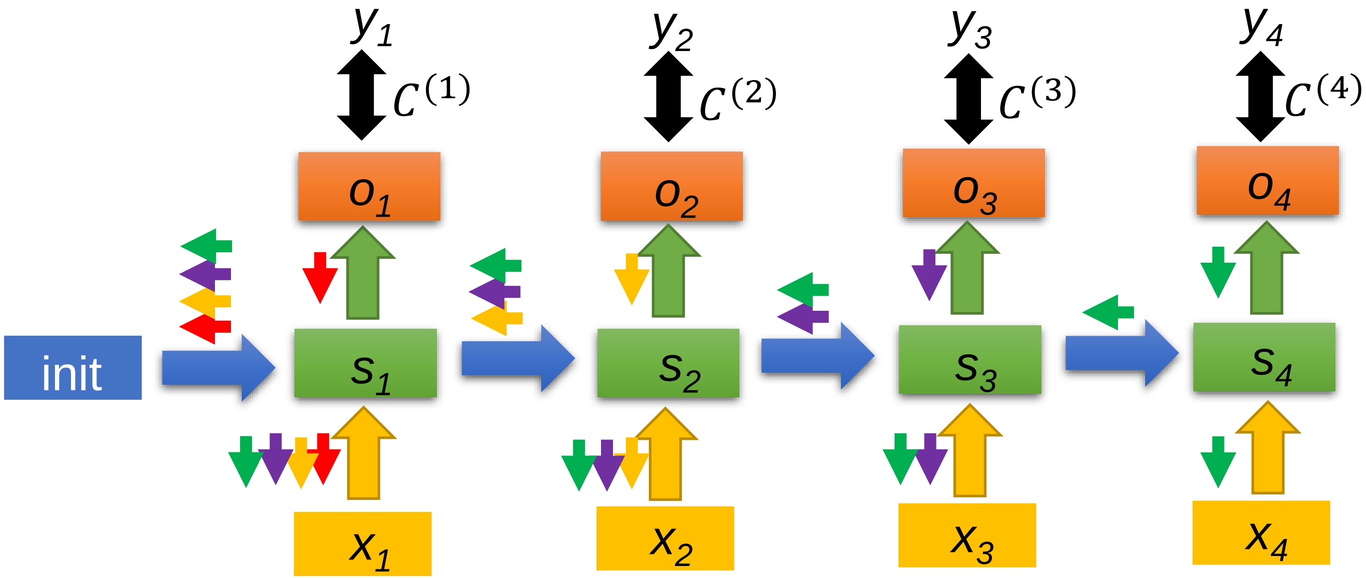
$$W^{(1)} \leftarrow W^{(1)} - \frac{\partial C(\theta)}{\partial W^{(1)}} - \frac{\partial C(\theta)}{\partial W^{(2)}}$$

Weights are tied together

BPTT

Forward Pass: Compute s_1, s_2, s_3, s_4 ……

Backward Pass: For $C^{(4)}$ For $C^{(3)}$ For $C^{(2)}$ For $C^{(1)}$



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RNN Training Issue

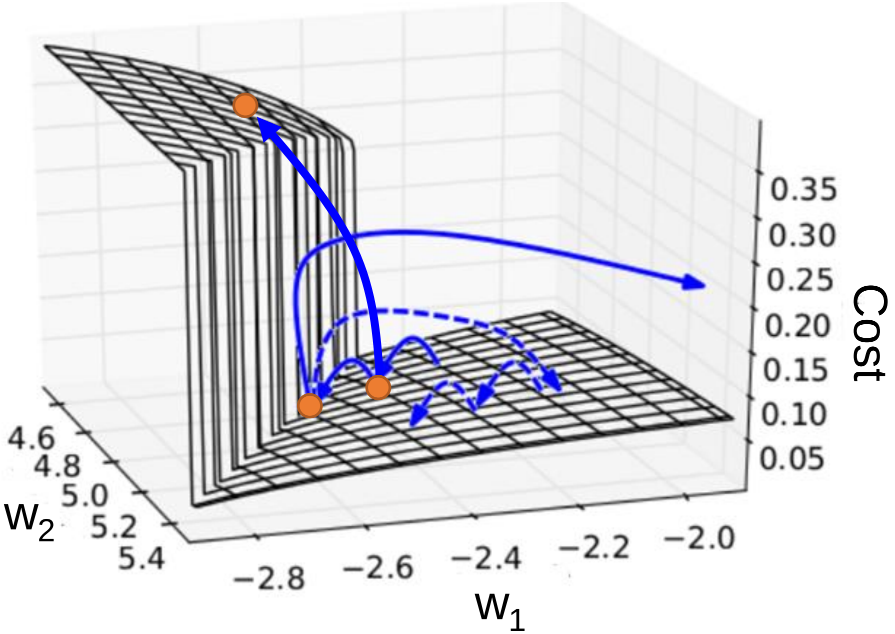
- The gradient is a product of Jacobian matrices, each associated with a step in the forward computation
- Multiply the <u>same</u> matrix at each time step during backprop

$$\delta^l = \sigma'(z^l) \odot \boxed{(W^{l+1})^T} \delta^{l+1}$$

The gradient becomes very small or very large quickly
→ **vanishing or exploding gradient**

Bengio et al., "Learning long-term dependencies with gradient descent is difficult," *IEEE Trans. of Neural Networks*, 1994. [link]
Pascanu et al., "On the difficulty of training recurrent neural networks," in *ICML*, 2013. [link]

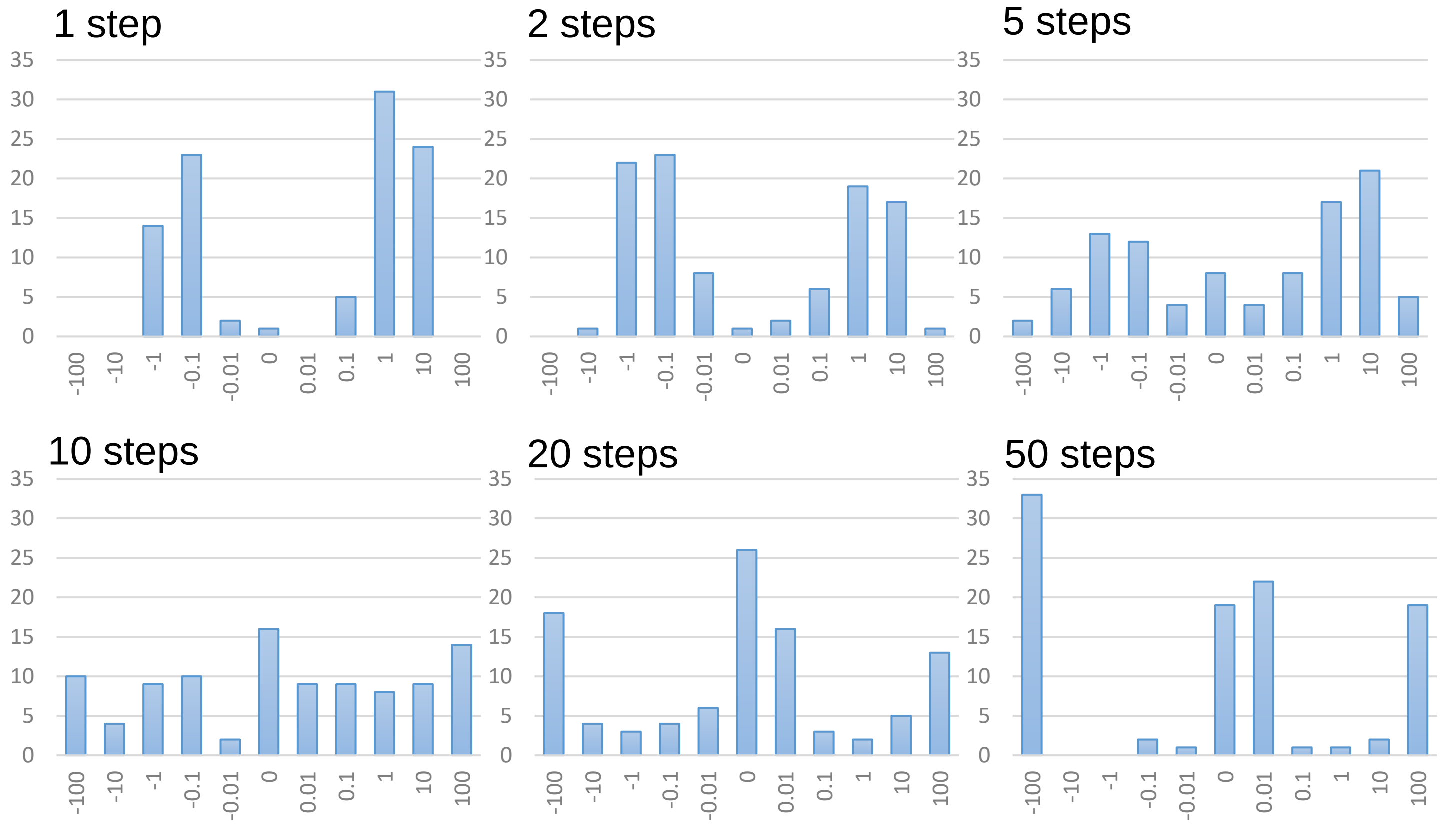
Rough Error Surface



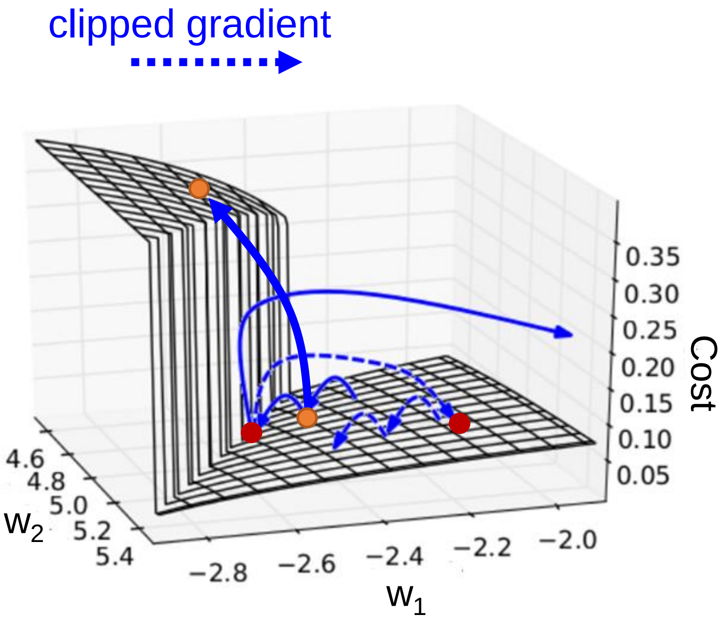
The error surface is either very flat or very steep

Bengio et al., “Learning long-term dependencies with gradient descent is difficult,” *IEEE Trans. of Neural Networks*, 1994. [link]
Pascanu et al., “On the difficulty of training recurrent neural networks,” in *ICML*, 2013. [link]

Vanishing/Exploding Gradient Example



Solution for Exploding Gradient: Clipping



Idea: control the gradient value to avoid exploding

Algorithm 1 Pseudo-code for norm clipping

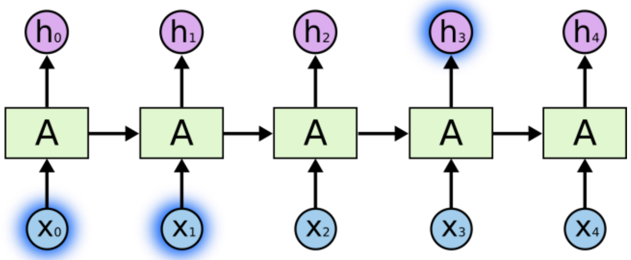
$\hat{\mathbf{g}} \leftarrow \frac{\partial \mathcal{E}}{\partial \theta}$
if $\|\hat{\mathbf{g}}\| \geq threshold$ **then**
  $\hat{\mathbf{g}} \leftarrow \frac{threshold}{\|\hat{\mathbf{g}}\|}\hat{\mathbf{g}}$
end if

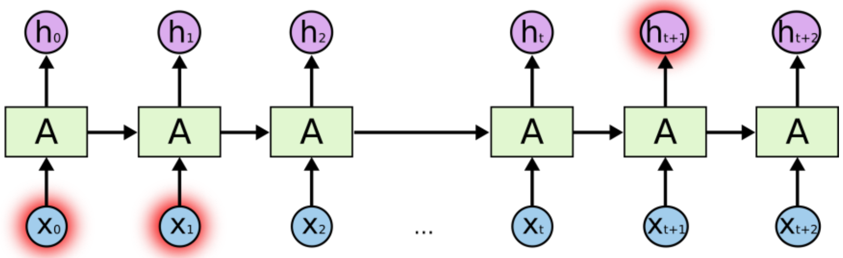
Parameter setting: values from half to ten times the average can still yield convergence

Pascanu et al., "On the difficulty of training recurrent neural networks," in *ICML*, 2013. [link]

Solution for Vanishing Gradient: Gating

- RNN models temporal sequence information
  - can handle "long-term dependencies" *in theory*

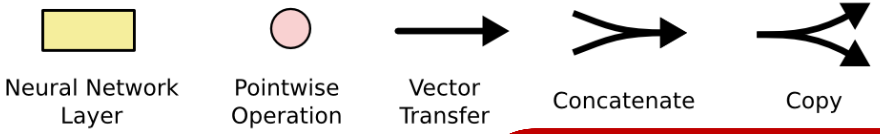




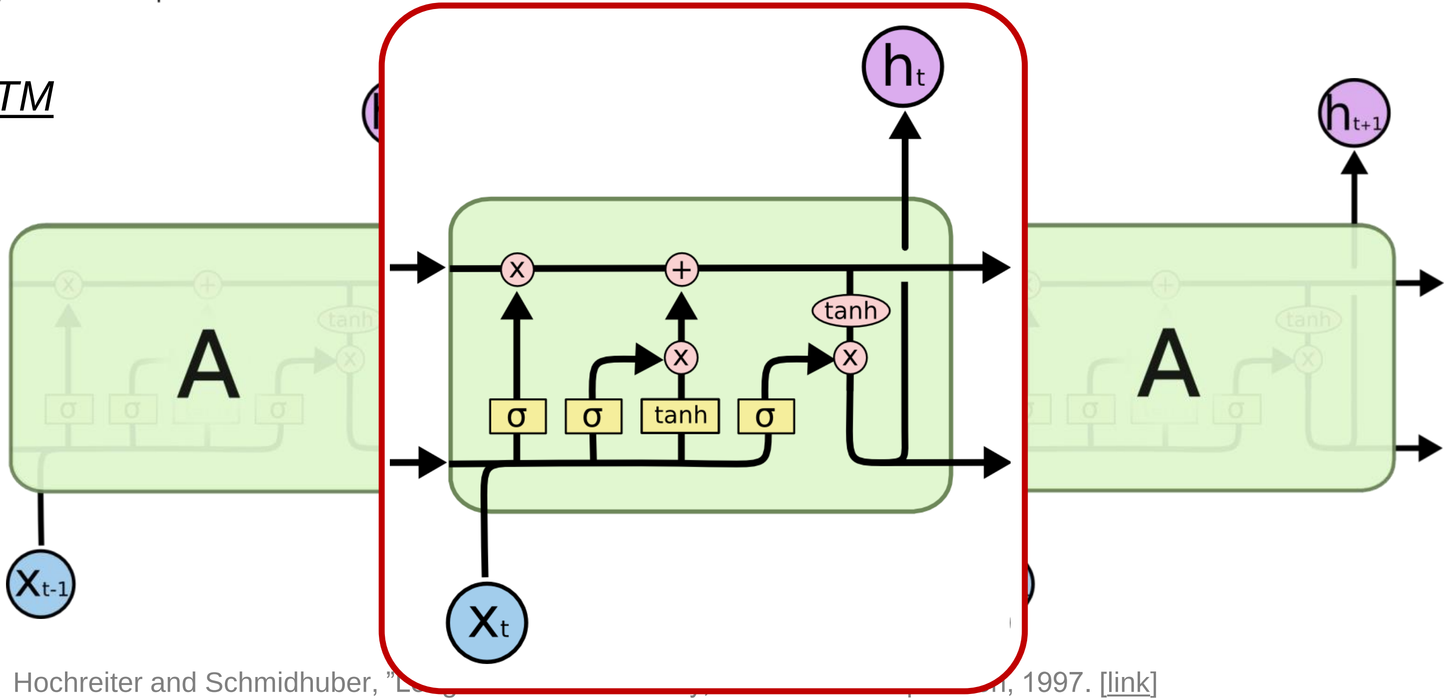
"I grew up in France…
I speak fluent *French*."

Issue: RNN cannot handle "long-term dependencies" due to vanishing gradient
→ gating directly encodes long-distance information

Long Short-Term Memory (LSTM)

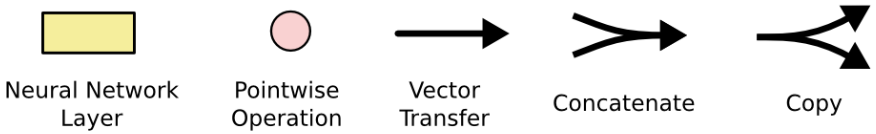


LSTM

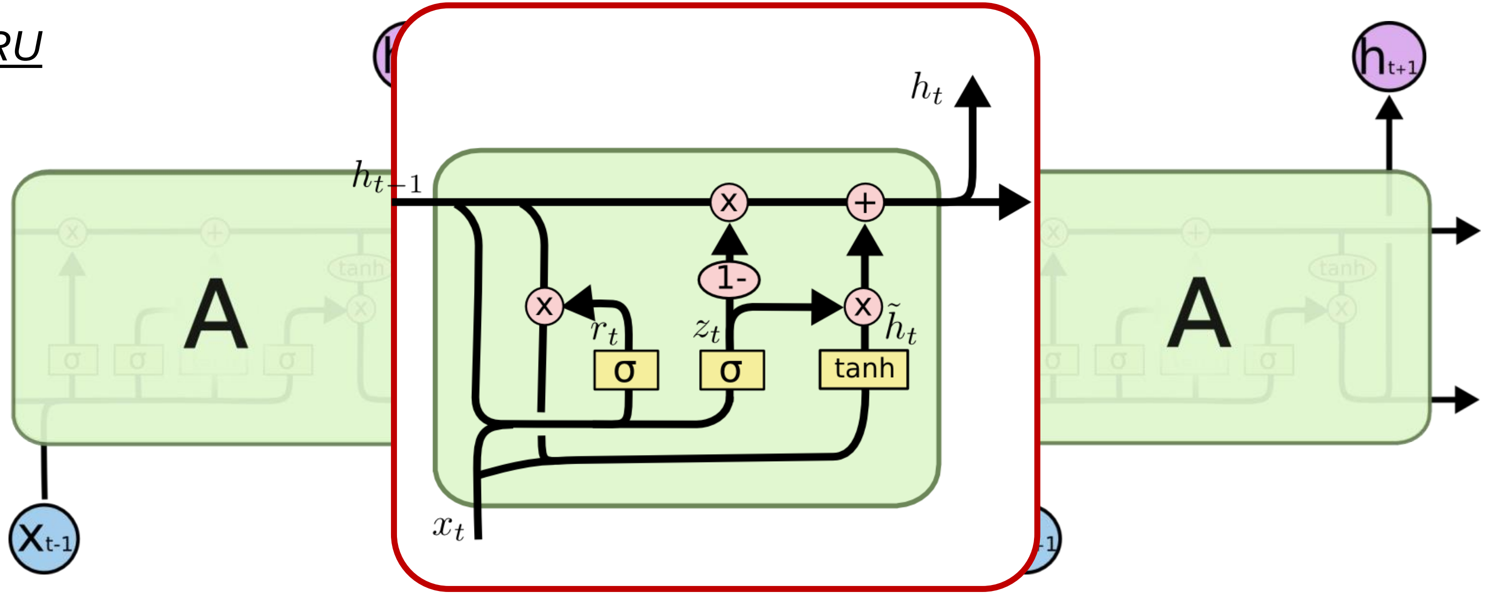


Hochreiter and Schmidhuber, ” … , 1997. [link]

Gated Recurrent Unit (GRU)

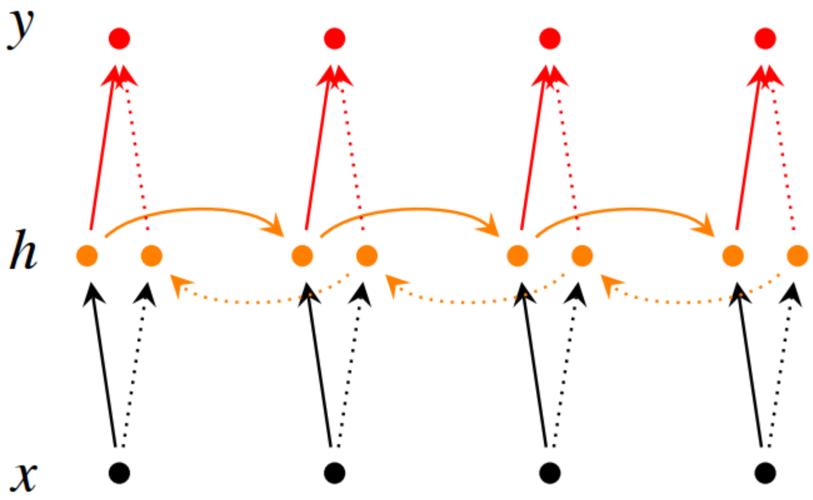


GRU



Cho et al., "Learning phrase representations using RNN encoder-decoder for statistical machine translation," arXiv preprint arXiv:1406.1078, 2014. [link]

Extension: Bidirectional RNN



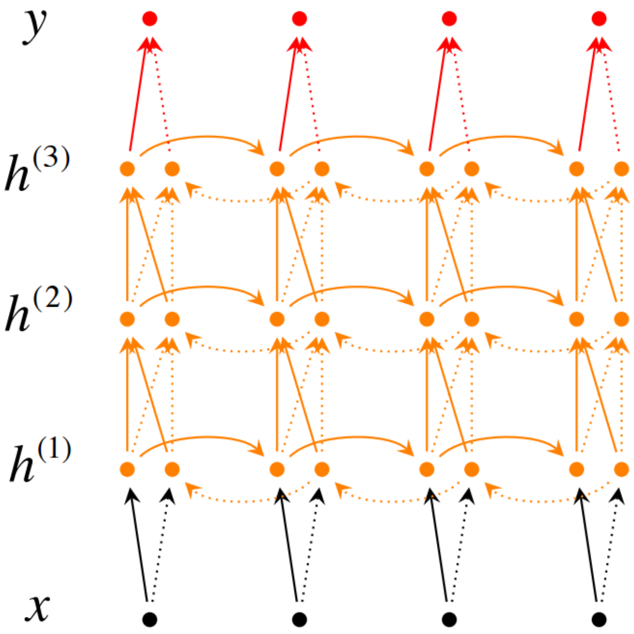
$$\overrightarrow{h}_t = f(\overrightarrow{W}x_t + \overrightarrow{V}\overrightarrow{h}_{t-1} + \overrightarrow{b})$$

$$\overleftarrow{h}_t = f(\overleftarrow{W}x_t + \overleftarrow{V}\overleftarrow{h}_{t+1} + \overleftarrow{b})$$

$$y_t = g(U[\overrightarrow{h}_t; \overleftarrow{h}_t] + c)$$

$h = [\overrightarrow{h}; \overleftarrow{h}]$ represents (summarizes) the past and future around a single token

Extension: Deep Bidirectional RNN



$$\overrightarrow{h}_t^{(i)} = f(\overrightarrow{W}^{(i)} h_t^{(i-1)} + \overrightarrow{V}^{(i)} \overrightarrow{h}_{t-1}^{(i)} + \overrightarrow{b}^{(i)})$$

$$\overleftarrow{h}_t^{(i)} = f(\overleftarrow{W}^{(i)} h_t^{(i-1)} + \overleftarrow{V}^{(i)} \overleftarrow{h}_{t+1}^{(i)} + \overleftarrow{b}^{(i)})$$

$$y_t = g(U[\overrightarrow{h}_t^{(L)}; \overleftarrow{h}_t^{(L)}] + c)$$

Each memory layer passes an intermediate representation to the next

RNN Applications
RNN各式應用情境

Outline

- Meaning Representations
  - Knowledge-Based Representation
  - Corpus-Based Representation
- Language Modeling
  - N-gram Language Model
  - Feed-Forward Neural Language Model
  - Recurrent Neural Network Language Model (RNNLM)
- Recurrent Neural Network
  - Definition
  - Training via Backpropagation through Time (BPTT)
  - Training Issue
  - Extension
- **RNN Applications**
  - Sequential Input
  - Sequential Output
    - Aligned Sequential Pairs (Tagging)
    - Unaligned Sequential Pairs (Seq2Seq/Encoder-Decoder)

How to Frame the Learning Problem?

- The learning algorithm f is to map the input domain X into the output domain Y

$$f : X \to Y$$

- Input domain: word, word sequence, audio signal, click logs
- Output domain: single label, sequence tags, tree structure, probability distribution

Network design should leverage input and output domain properties

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Input Domain – Sequence Modeling

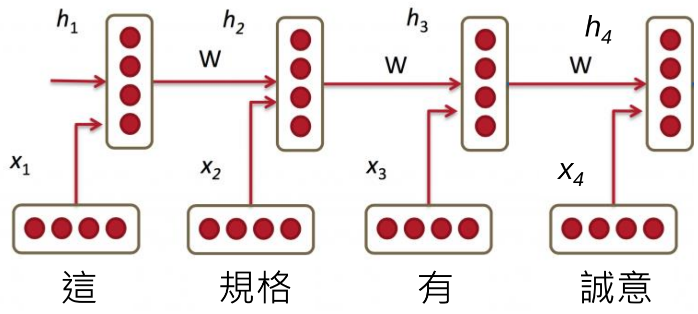
- Idea: aggregate the meaning from all words into a vector
- Method:
  - Basic combination: average, sum
  - Neural combination:
    - ✓ Recursive neural network (RvNN)
    - ✓ Recurrent neural network (RNN)
    - ✓ Convolutional neural network (CNN)
    - ✓ Transformer

$$\begin{array}{cl}
 & \overbrace{\hphantom{\begin{bmatrix}0.2 & 0.6 & 0.3 & \cdots & 0.4\end{bmatrix}}}^{N\text{-dim}} \\
\text{這 (this)} & \begin{bmatrix}0.2 & 0.6 & 0.3 & \cdots & 0.4\end{bmatrix} \\
\text{規格 (specification)} & \begin{bmatrix}0.9 & 0.8 & 0.1 & \cdots & 0.1\end{bmatrix} \\
\text{有 (have)} & \begin{bmatrix}0.1 & 0.3 & 0.1 & \cdots & 0.7\end{bmatrix} \\
\text{誠意 (sincerity)} & \begin{bmatrix}0.5 & 0.0 & 0.6 & \cdots & 0.4\end{bmatrix}
\end{array}$$

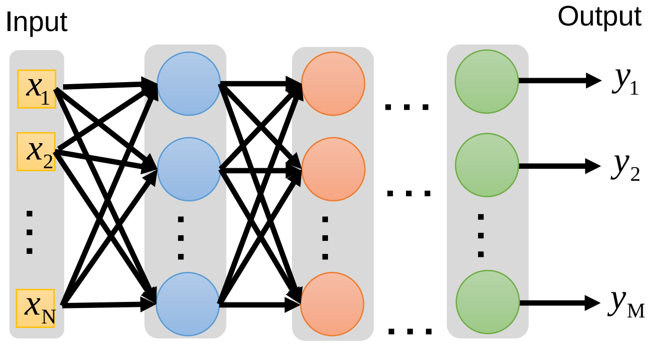
How to compute $\vec{x} = \begin{bmatrix}x_1 & x_2 & x_3 & \cdots & x_N\end{bmatrix}$

Sentiment Analysis

- Encode the sequential input into a vector using RNN



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



RNN considers temporal information to learn sentence vectors as classifier's input

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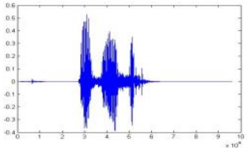
Output Domain – Sequence Prediction

- POS Tagging

“推薦我台大後門的餐廳” → 推薦/VV 我/PN 台大/NR 後門/NN 的/DEG 餐廳/NN

- Speech Recognition



→ “大家好”

- Machine Translation

“How are you doing today?” → “你好嗎?”

The output can be viewed as a sequence of classification

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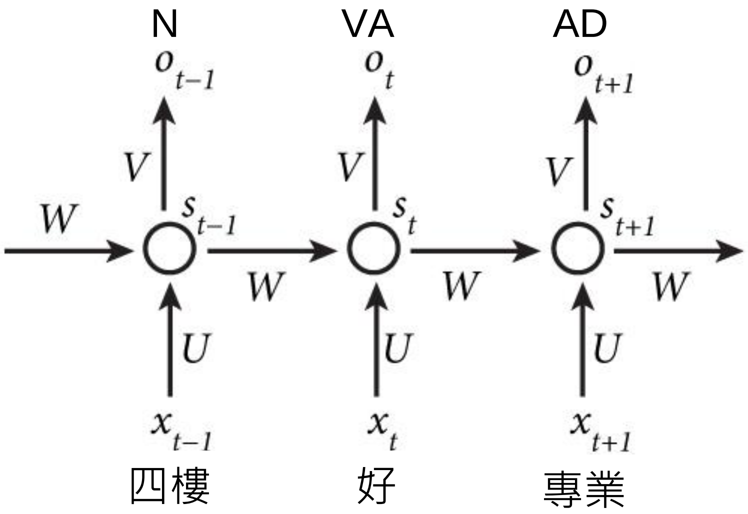
    - Unaligned Sequential Pairs (Seq2Seq/Encoder-Decoder)

POS Tagging

- Tag a word at each timestamp
  - Input: word sequence
  - Output: corresponding POS tag sequence



Natural Language Understanding (NLU)

- Tag a word at each timestamp
  - Input: word sequence
  - Output: IOB-format slot tag and intent tag

<START>	just	sent	email	to	bob	about	fishing	this	weekend	<END>
O	O	O	O	O	B-contact_name	O	B-subject	I-subject	I-subject	send_email

→ send_email(contact_name="bob", subject="fishing this weekend")

Temporal orders for input and output are the same

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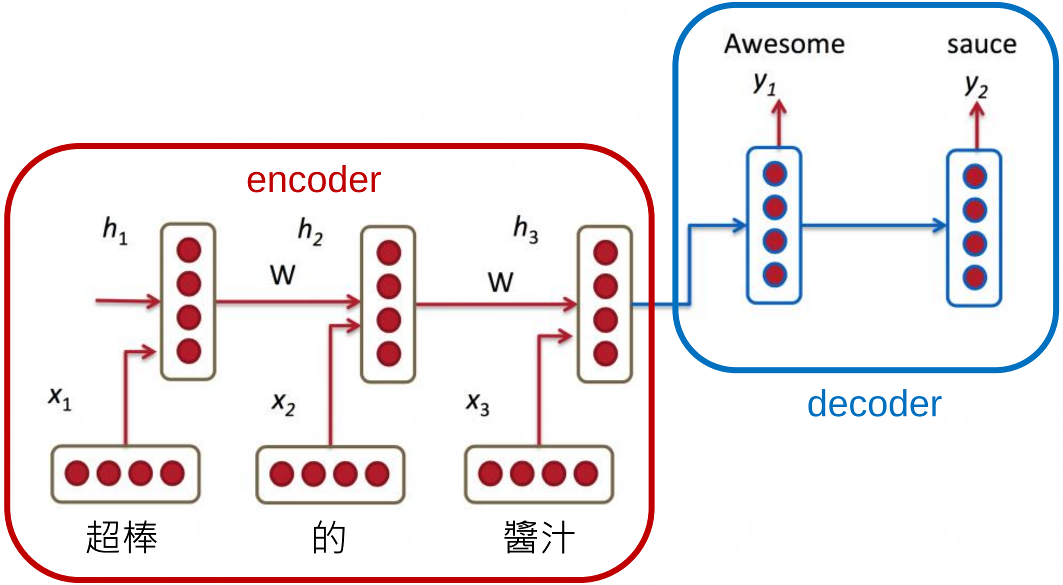
    - **Unaligned Sequential Pairs (Seq2Seq/Encoder-Decoder)**

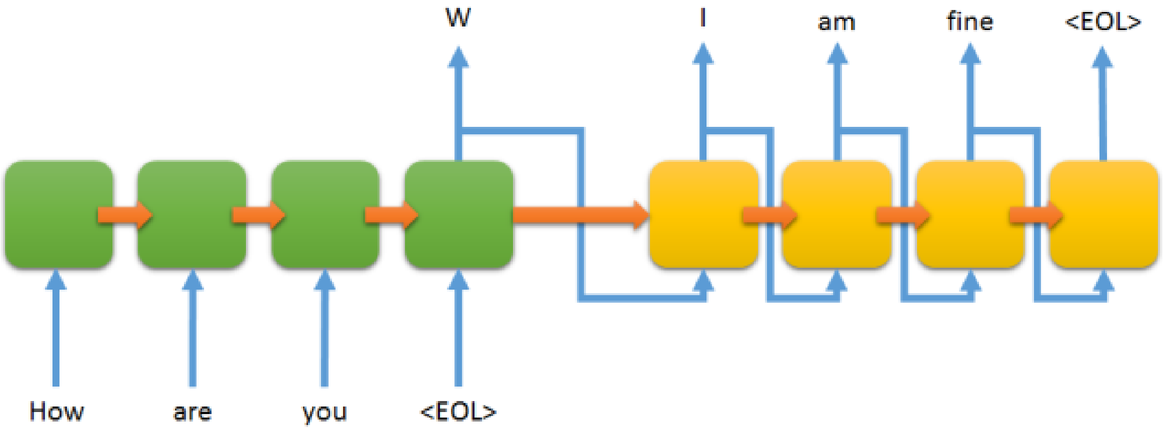
Machine Translation

- Cascade two RNNs, one for encoding and one for decoding
  - Input: word sequences in the source language
  - Output: word sequences in the target language



Chit-Chat Dialogue Modeling

- Cascade two RNNs, one for encoding and one for decoding
  - Input: word sequences in the question
  - Output: word sequences in the response



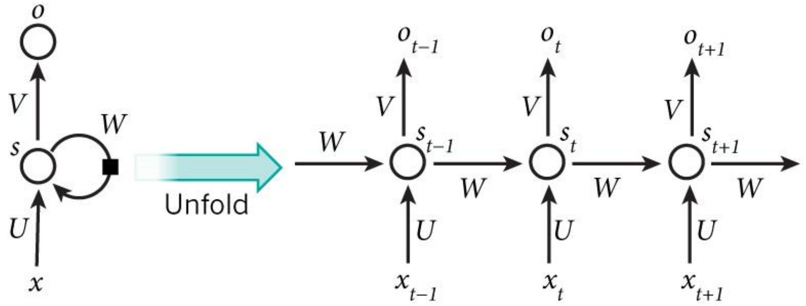
Temporal ordering for input and output may be different

Concluding Remarks

- Word Representations
  - Corpus-Based Representation
- Language Modeling
  - RNNLM
- Recurrent Neural Networks
  - Definition

$$s_t = \sigma(W s_{t-1} + U x_t)$$

$$o_t = \mathrm{softmax}(V s_t)$$



  - Backpropagation through Time (BPTT)
  - Vanishing/Exploding Gradient
- RNN Applications
  - Sequential Input: Sequence-Level Embedding
  - Sequential Output: Tagging / Seq2Seq (Encoder-Decoder)