

Sequence Modeling

NLP and Sequential Data

- NLP is full of sequential data
 - Words in sentences
 - Characters in words
 - Sentences in discourse
 - ...

Long-distance Dependencies in Language

- Agreement in number, gender, etc.

He does not have very much confidence in **himself**.

She does not have very much confidence in **herself**.

- Selectional preference

The **reign** has lasted as long as the life of the **queen**.

The **rain** has lasted as long as the life of the **clouds**.

Can be Complicated!

- What is the referent of “it”?

The trophy would not fit in the brown suitcase because it was too **big**.

Trophy

The trophy would not fit in the brown suitcase because it was too **small**.

Suitcase

(from Winograd Schema Challenge:

<http://commonsensereasoning.org/winograd.html>)

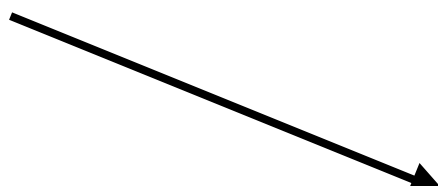
Types of Sequential Prediction Problems

Types of Prediction: Binary, Multi-class, Structured

- Two classes (**binary classification**)

I hate this movie  positive
negative

- Multiple classes (**multi-class classification**)

I hate this movie  very good
good
neutral
bad
very bad

- Exponential/infinite labels (**structured prediction**)

I hate this movie  PRP VBP DT NN

I hate this movie  *kono eiga ga kirai*

Types of Prediction: Unconditioned vs. Conditioned

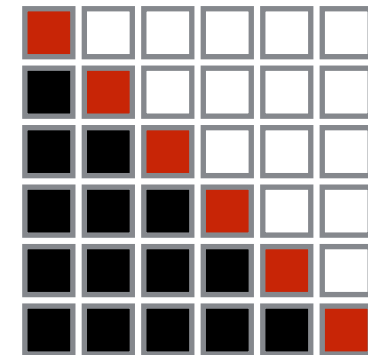
- **Unconditioned Prediction:** Predict the probability of a single variable $P(X)$
- **Conditioned Prediction:** Predict the probability of an output variable given an input $P(Y|X)$

Types of Unconditioned Prediction

Left-to-right Autoregressive Prediction

$$P(X) = \prod_{i=1}^{|X|} P(x_i | x_1, \dots, x_{i-1})$$

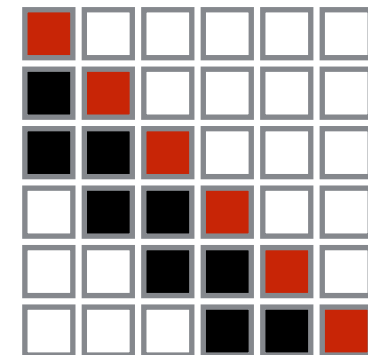
(e.g. RNN or Transformer LM)



Left-to-right Markov Chain (order n-1)

$$P(X) = \prod_{i=1}^{|X|} P(x_i | x_{i-n+1}, \dots, x_{i-1})$$

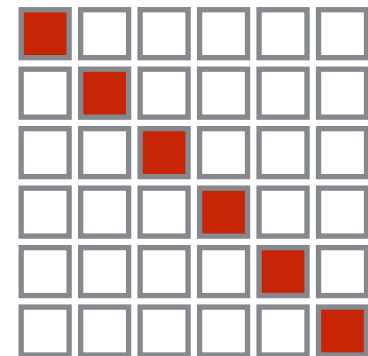
(e.g. n-gram LM, feed-forward LM)



Independent Prediction

$$P(X) = \prod_{i=1}^{|X|} P(x_i)$$

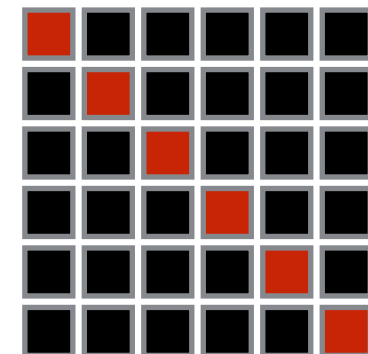
(e.g. unigram model)



Bidirectional Prediction

$$P(X) \neq \prod_{i=1}^{|X|} P(x_i | x_{\neq i})$$

(e.g. masked language model)



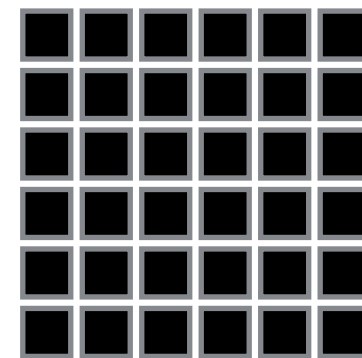
Types of Conditioned Prediction

Autoregressive Conditioned Prediction

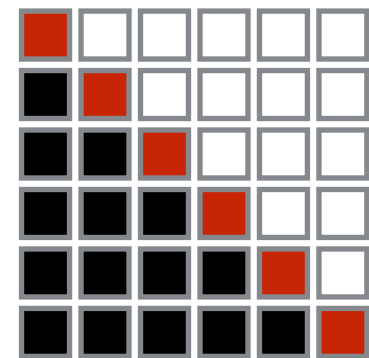
$$P(Y|X) = \prod_{i=1}^{|Y|} P(y_i|X, y_1, \dots, y_{i-1})$$

(e.g. seq2seq model)

Source X



Target Y

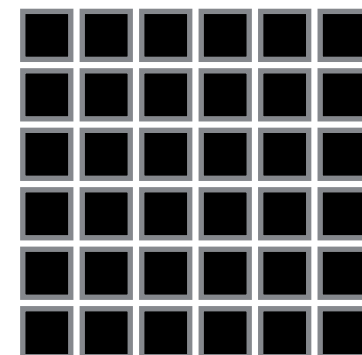


Non-autoregressive Conditioned Prediction

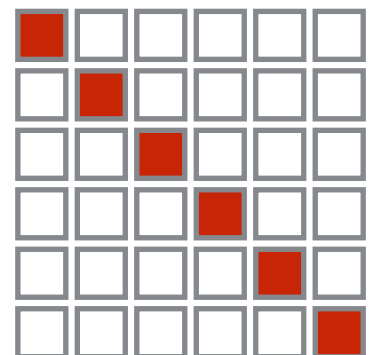
$$P(Y|X) = \prod_{i=1}^{|Y|} P(y_i|X)$$

(e.g. sequence labeling, non-autoregressive MT)

Source X



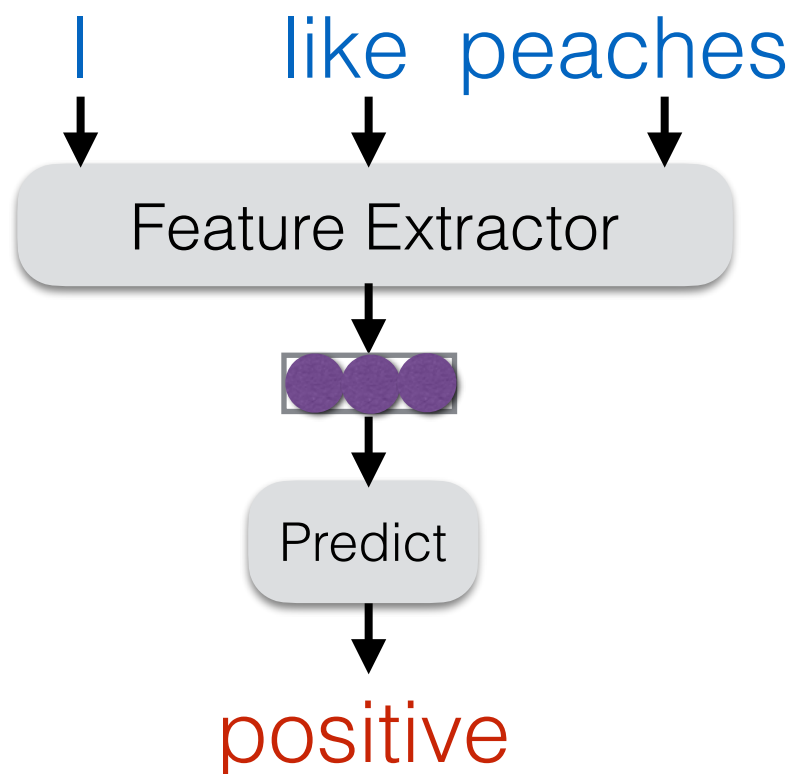
Target Y



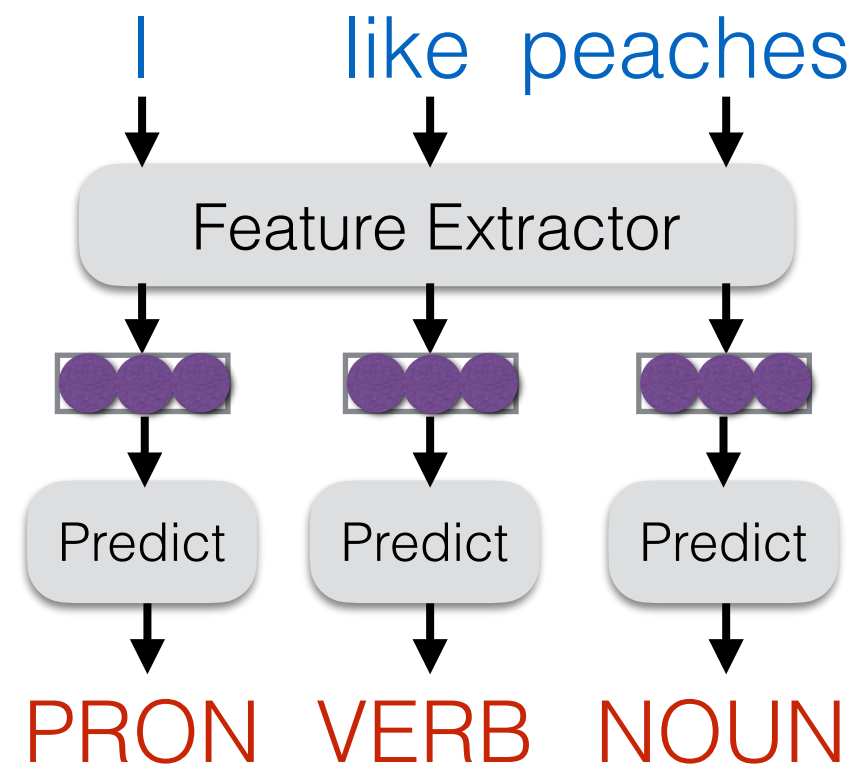
Basic Modeling Paradigm: Extract Features -> Predict

- Given an input text X
- Extract features H
- Predict labels Y

Text Classification



Sequence Labeling

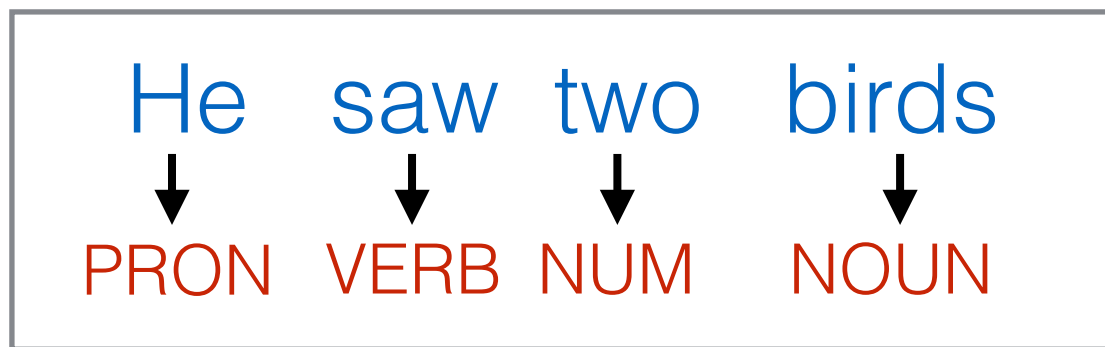


An Aside: More on Sequence Labeling

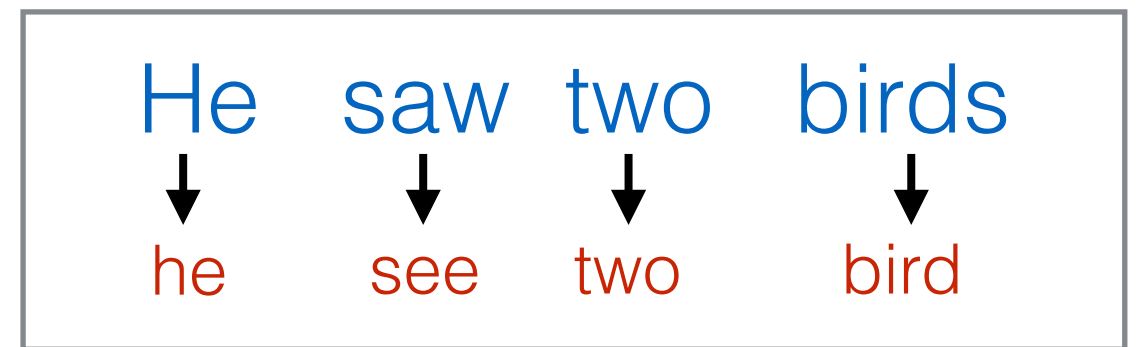
Sequence Labeling

- Given an input text X , predict an output label sequence Y of equal length!

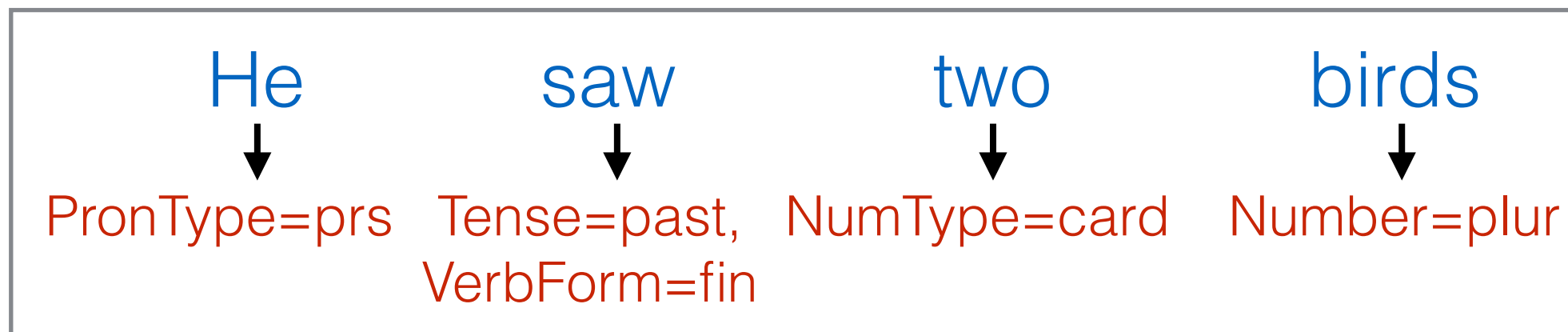
Part of Speech Tagging



Lemmatization



Morphological Tagging



... and more!

Span Labeling

- Given an input text X , predict an output spans and labels Y .

Named Entity Recognition

Graham Neubig is teaching at Carnegie Mellon University
PER ORG

Syntactic Chunking

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NP VP NP

Semantic Role Labeling

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Actor Predicate Location

... and more!

Span Labeling as Sequence Labeling

- Predict **B**eginning, **I**n, and **O**ut tags for each word in a span

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PER ORG

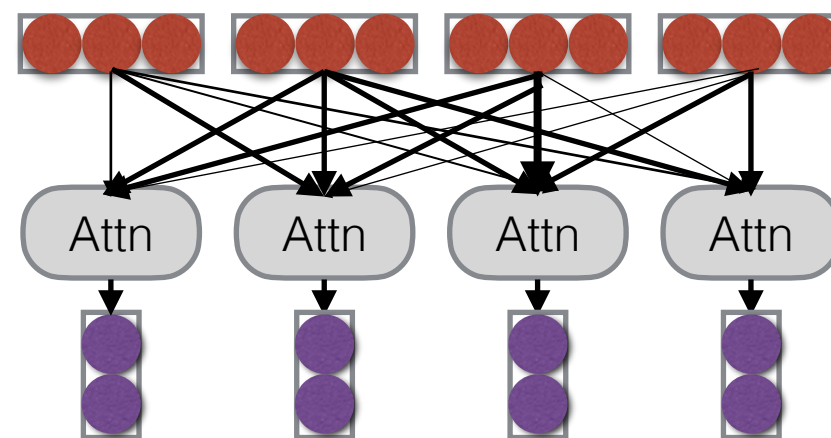
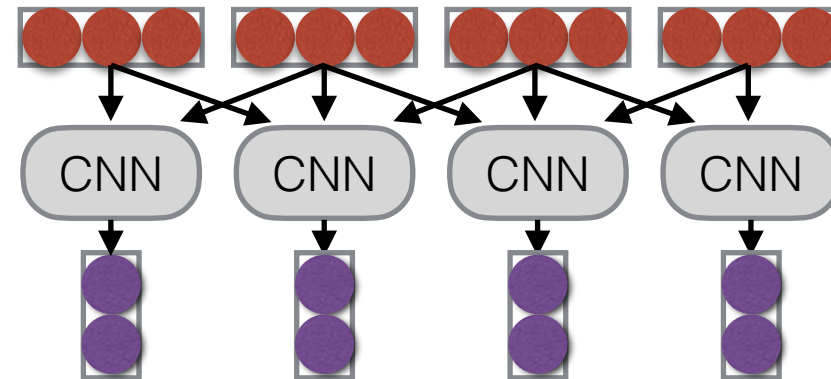
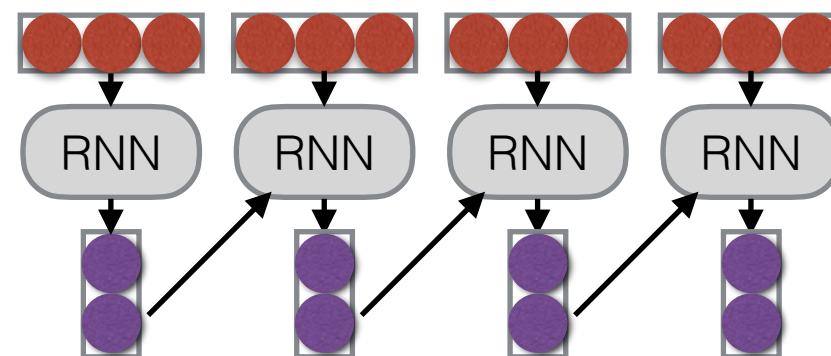
Graham Neubig is teaching at Carnegie Mellon University

B-PER I-PER O O O B-ORG I-ORG I-ORG

Types of Sequence Models

Three Major Types of Sequence Models

- **Recurrence:** Condition representations on an encoding of the history
- **Convolution:** Condition representations on local context
- **Attention:** Condition representations on a weighted average of all tokens



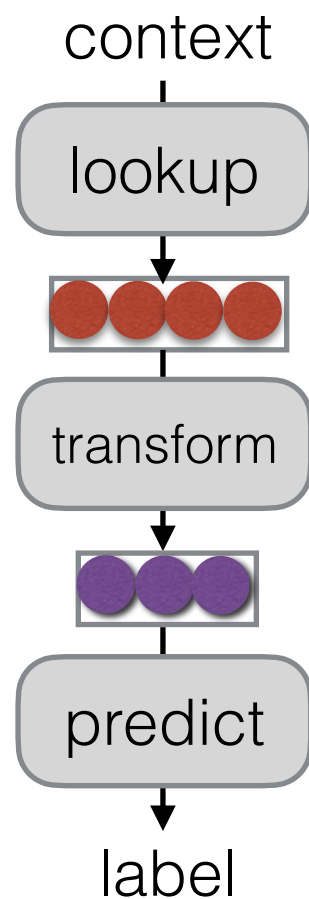
A Sequence Model: Recurrent Neural Networks

Recurrent Neural Networks

(Elman 1990)

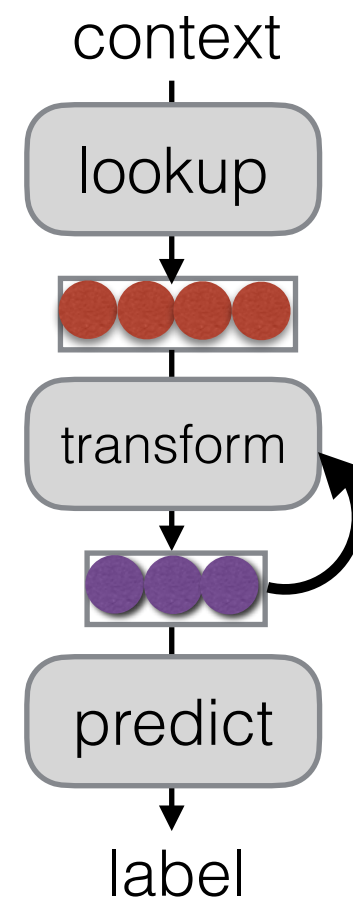
- Tools to “remember” information

Feed-forward NN



$$h_t = f(W_x x_t + b)$$

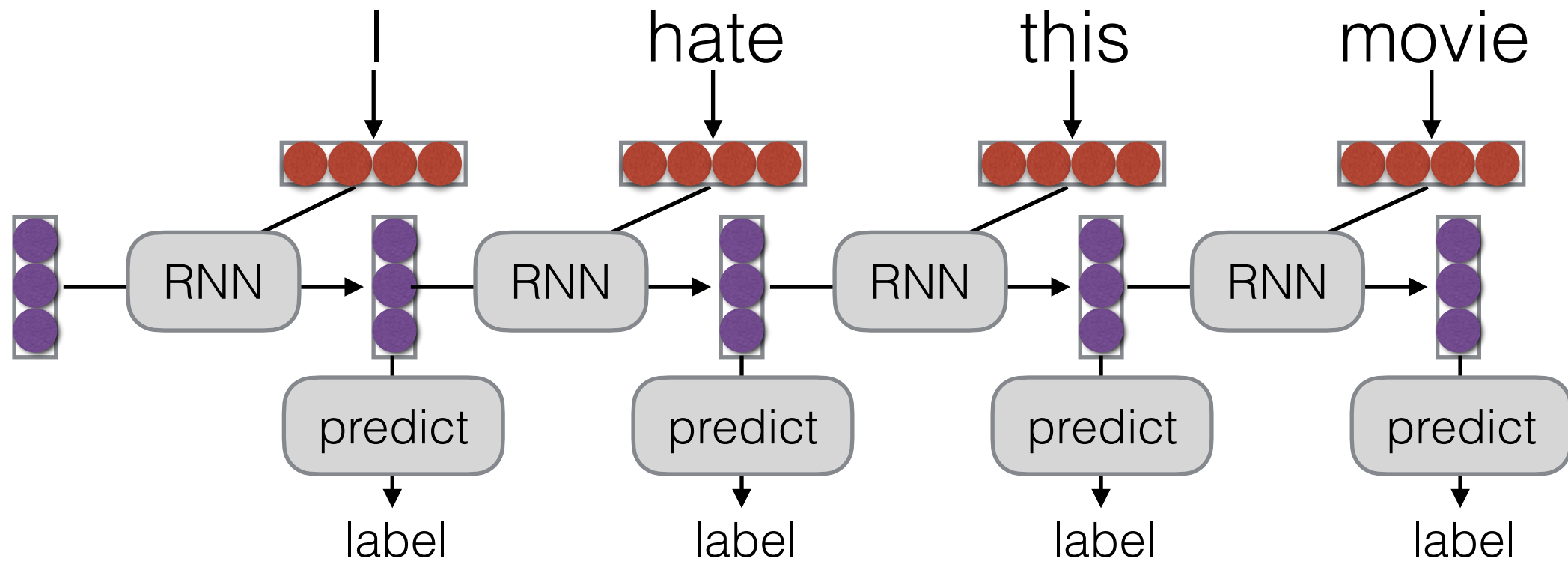
Recurrent NN



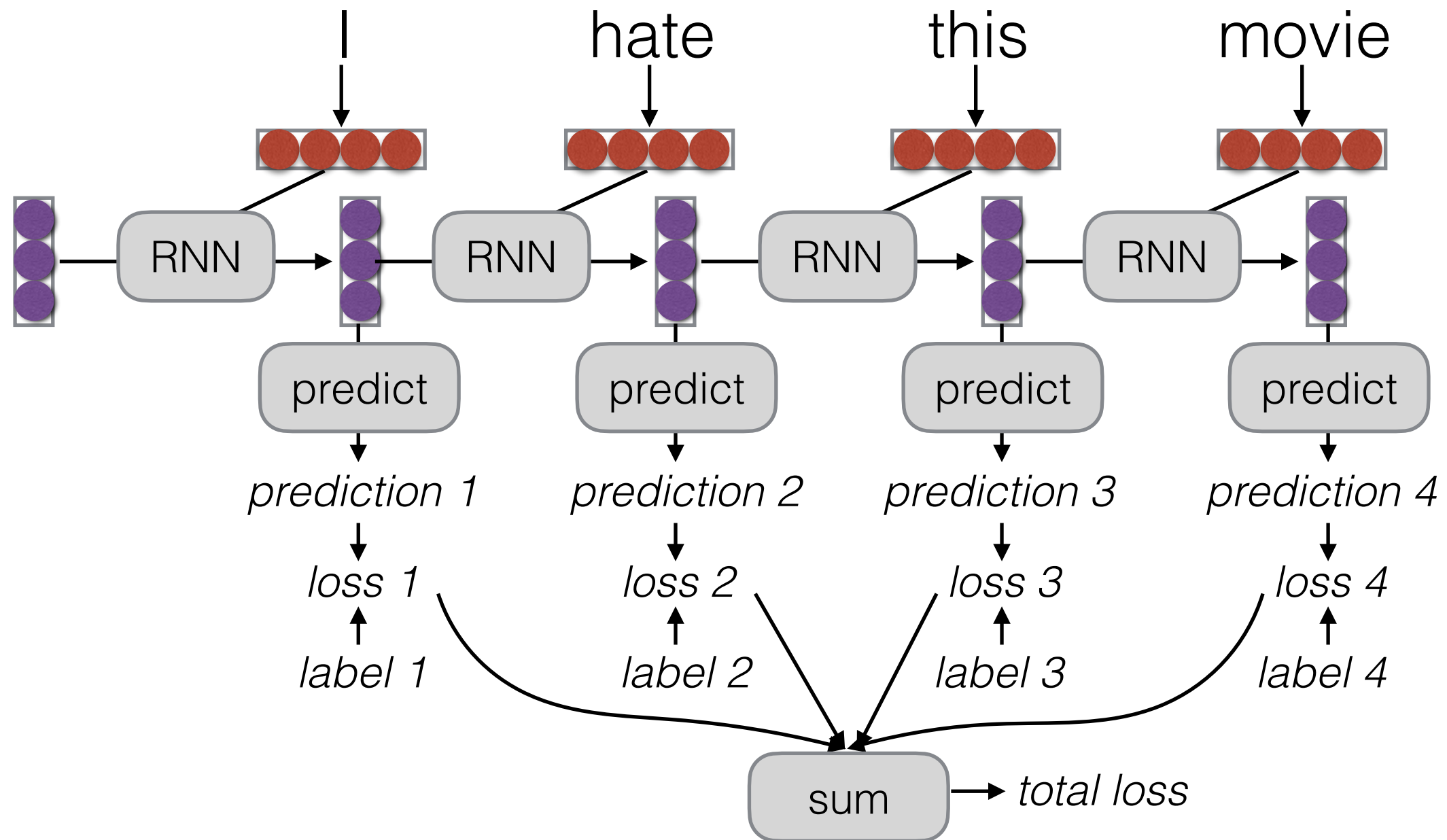
$$h_t = f(W_h h_{t-1} + W_x x_t + b)$$

Unrolling in Time

- What does processing a sequence look like?

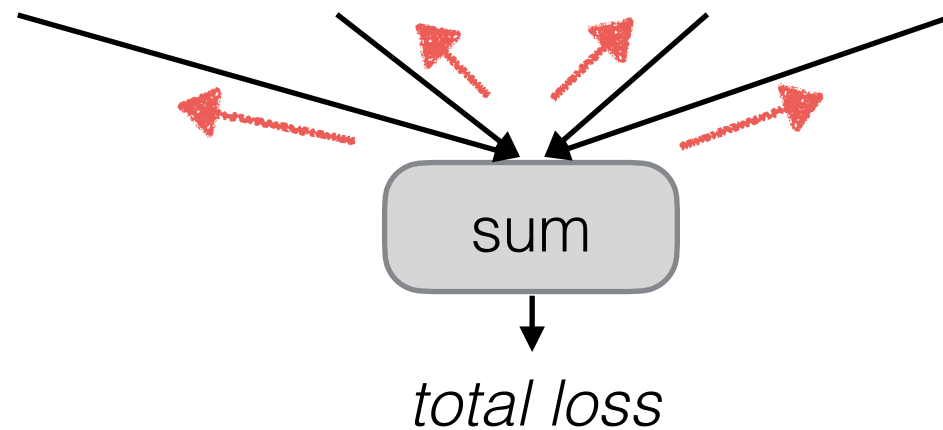


Training RNNs



RNN Training

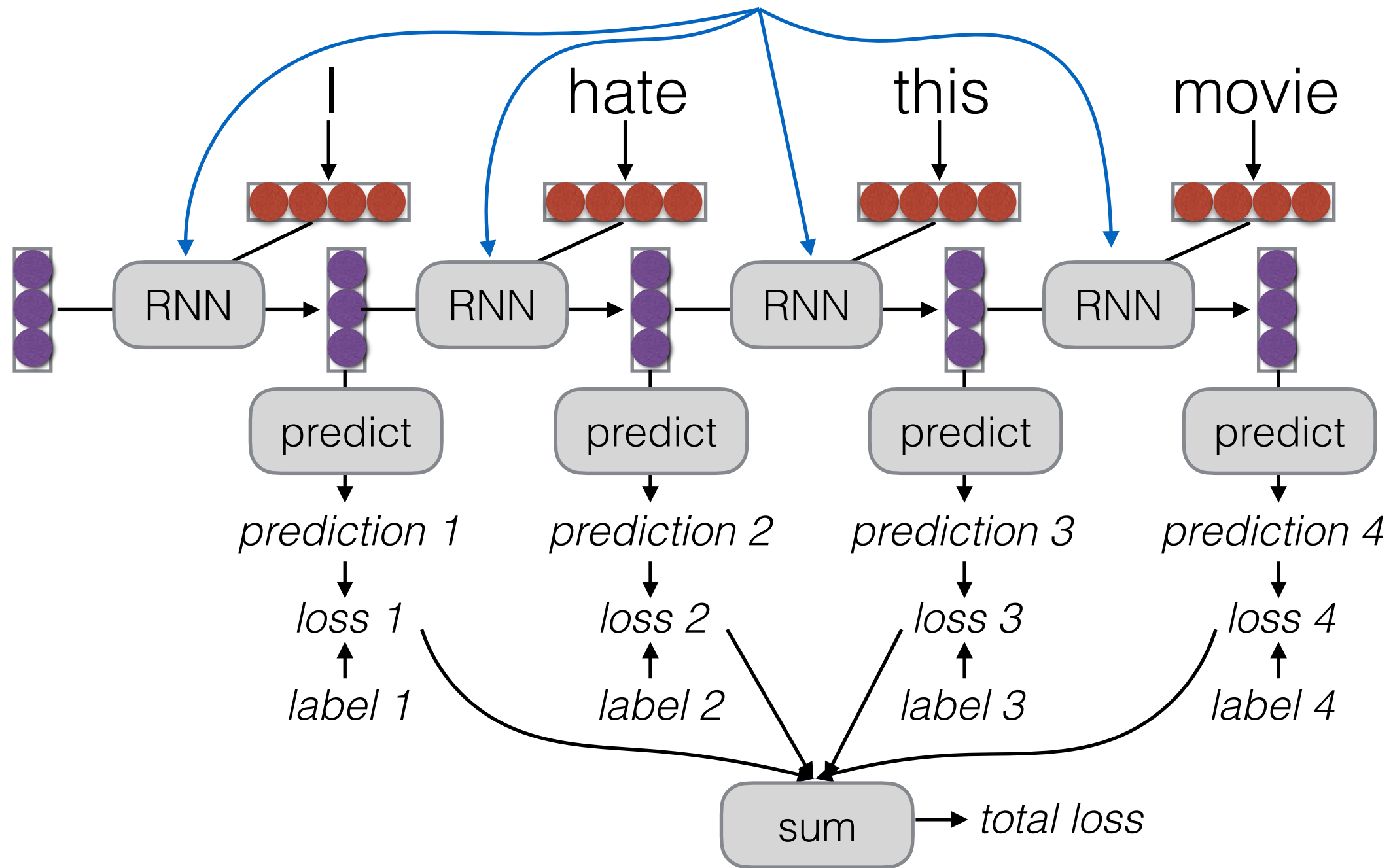
- The unrolled graph is a well-formed (DAG) computation graph—we can run backprop



- Parameters are tied across time, derivatives are aggregated across all time steps
- This is historically called “backpropagation through time” (BPTT)

Parameter Tying

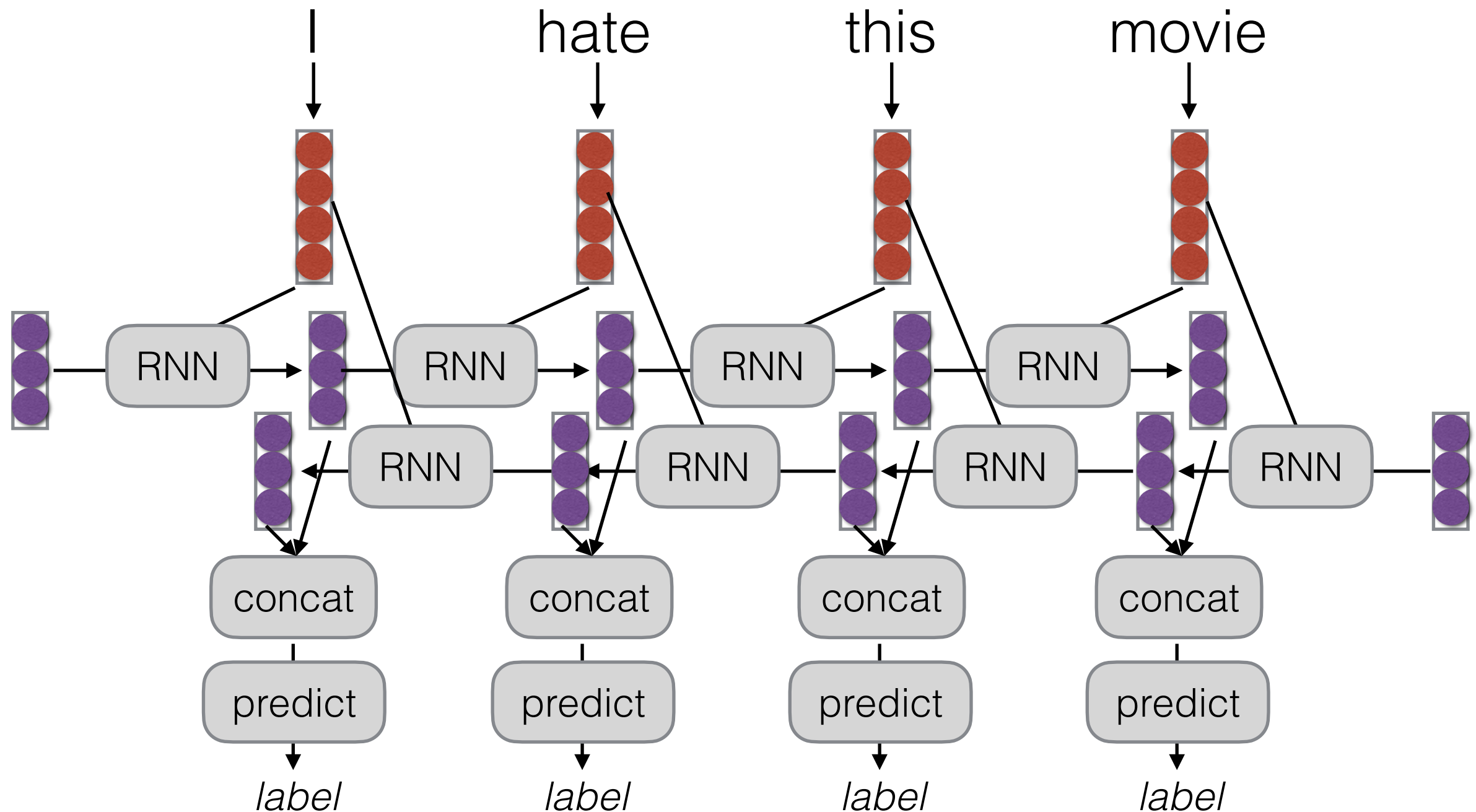
Parameters are shared! Derivatives are accumulated.



(Same for attention, convolutional networks)

Bi-RNNs

- A simple extension, run the RNN in both directions

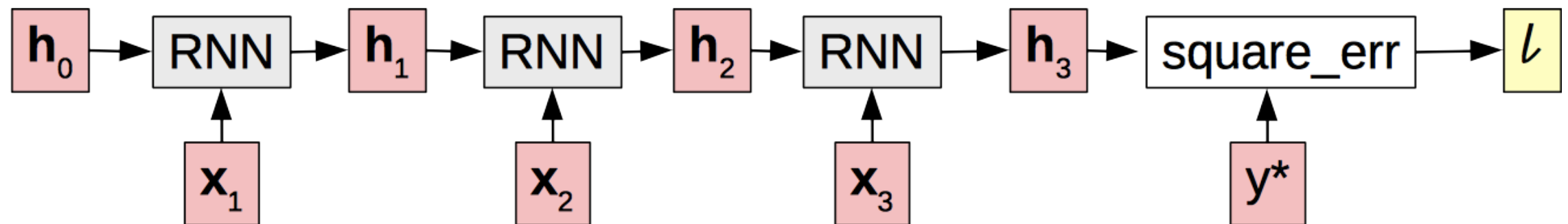


Vanishing Gradients

Vanishing Gradient

- Gradients decrease as they get pushed back

$$\frac{dl}{dh_0} = \text{tiny} \quad \frac{dl}{dh_1} = \text{small} \quad \frac{dl}{dh_2} = \text{med.} \quad \frac{dl}{dh_3} = \text{large}$$



- Why? “Squashed” by non-linearities or small weights in matrices.

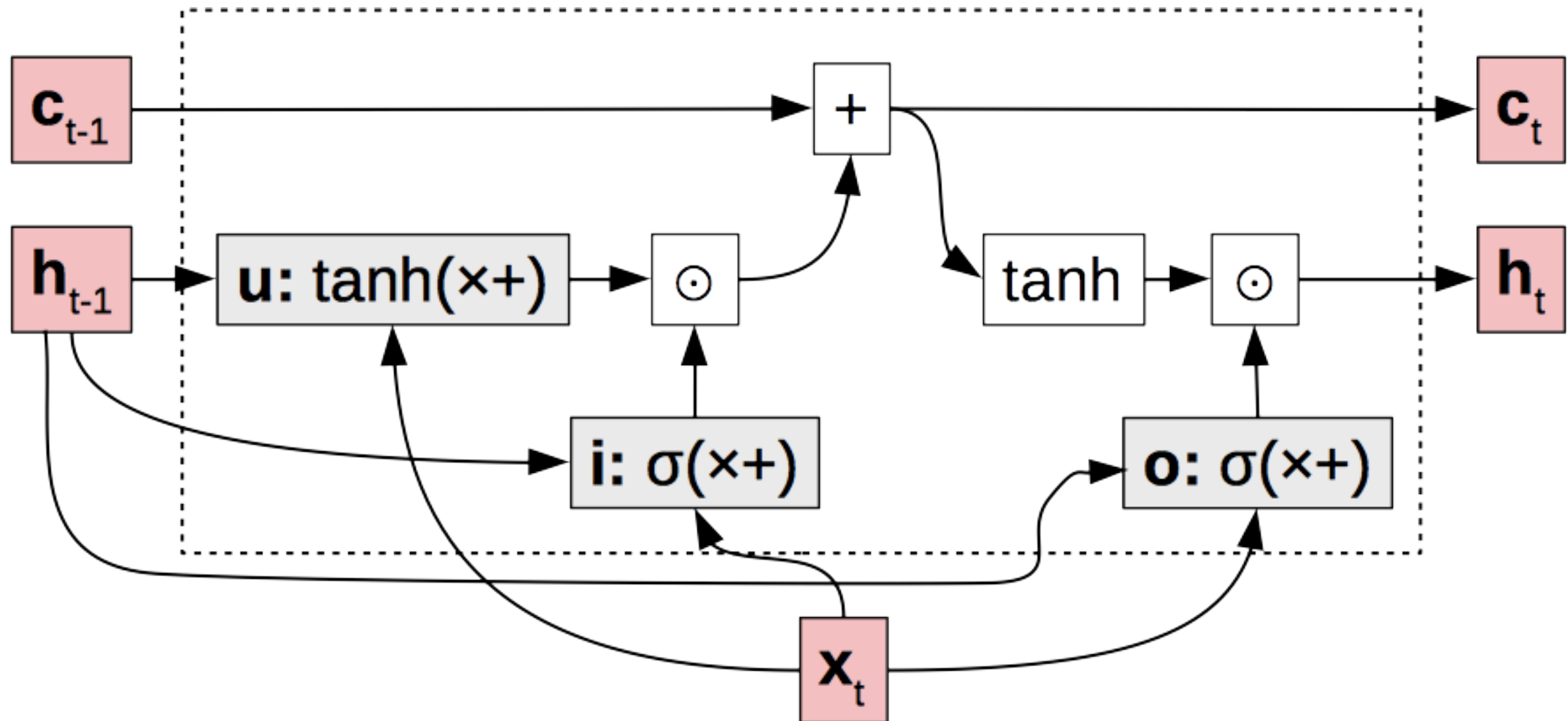
A Solution:

Long Short-term Memory

(Hochreiter and Schmidhuber 1997)

- **Basic idea:** make additive connections between time steps
- Addition does not modify the gradient, no vanishing
- Gates to control the information flow

LSTM Structure

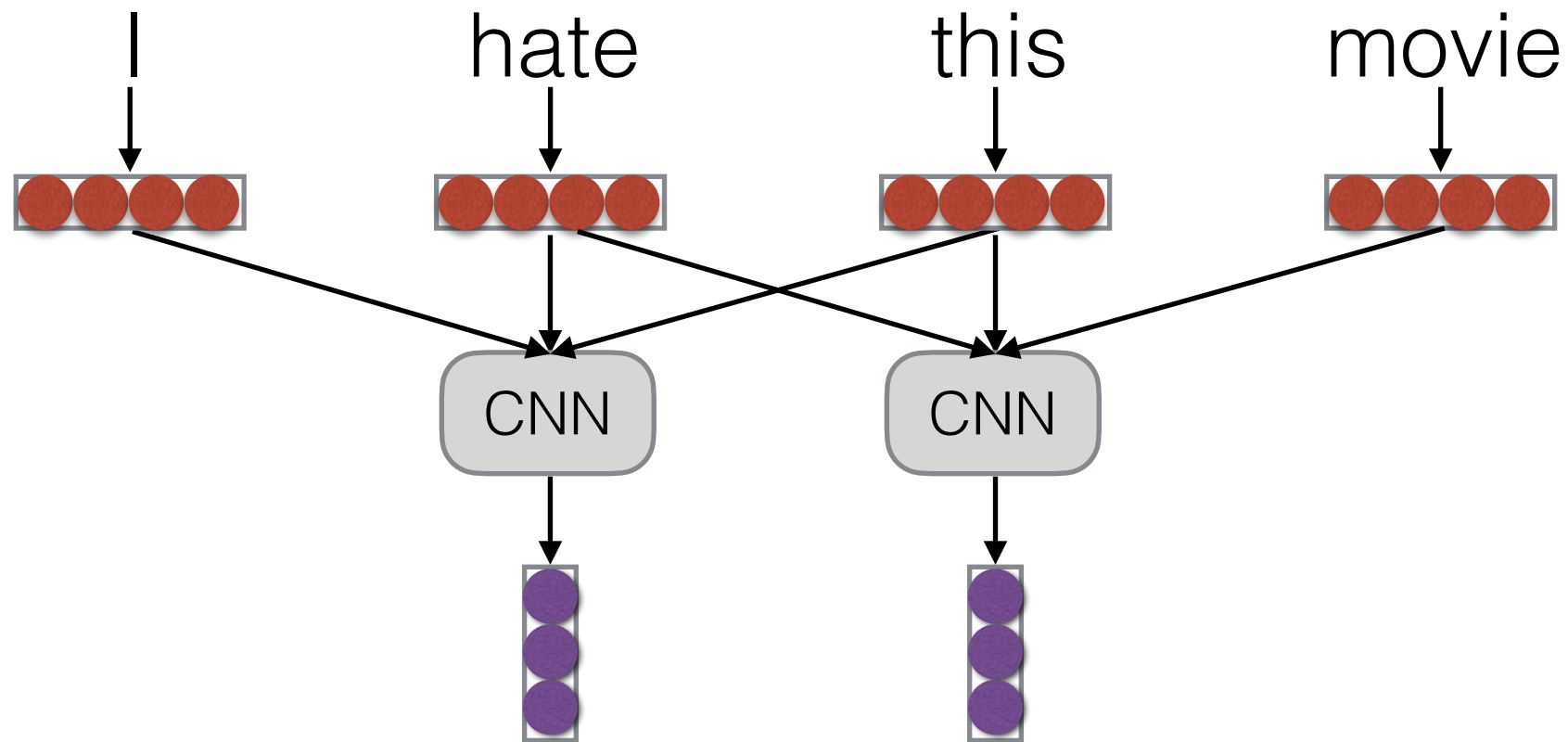


update **u**: what value do we try to add to the memory cell?
input **i**: how much of the update do we allow to go through?
output **o**: how much of the cell do we reflect in the next state?

Convolution

Convolution

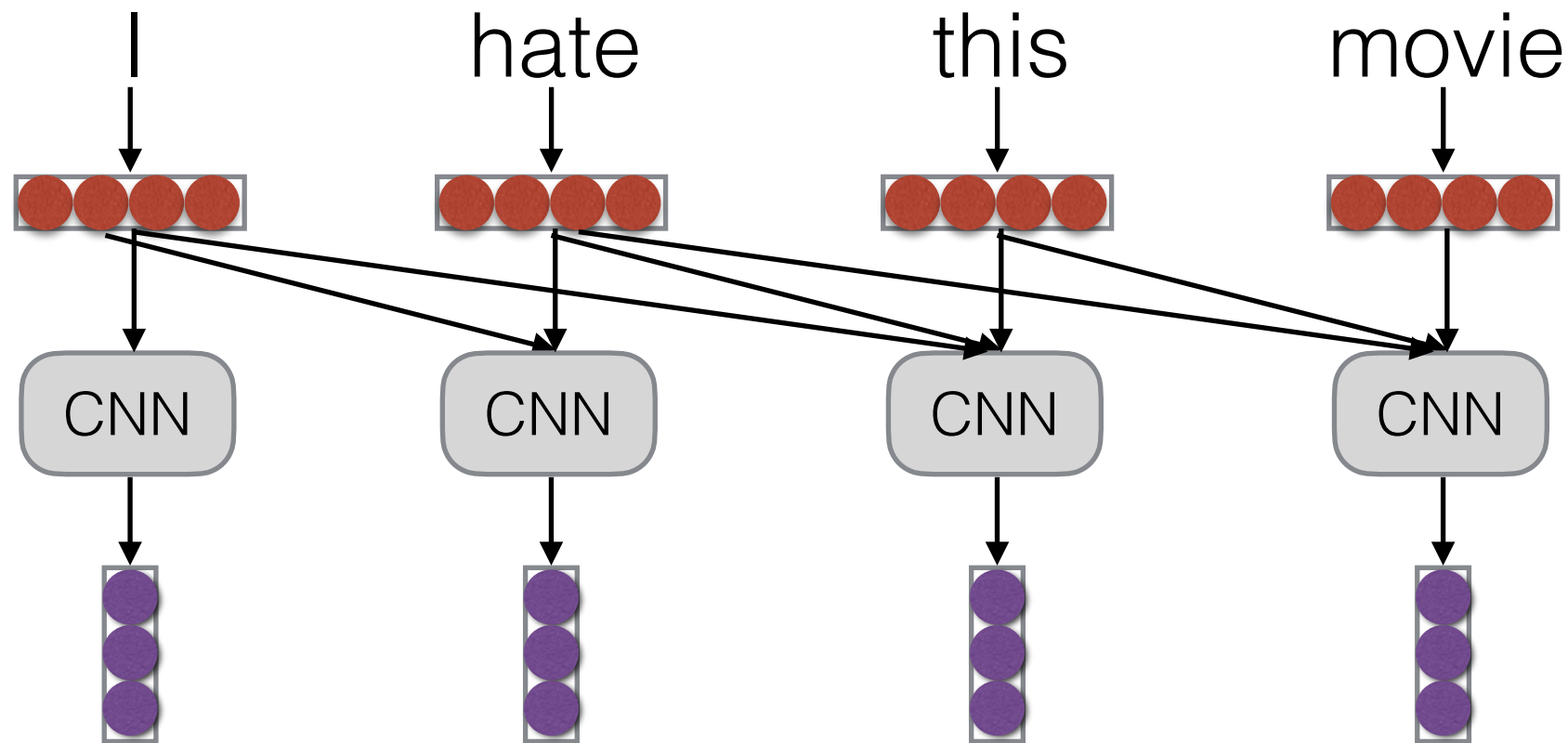
- Calculate based on local context



$$h_t = f(W[x_{t-1}; x_t; x_{t+1}])$$

Convolution for Auto-regressive Models

- Functionally identical, just consider previous context



Attention

Basic Idea

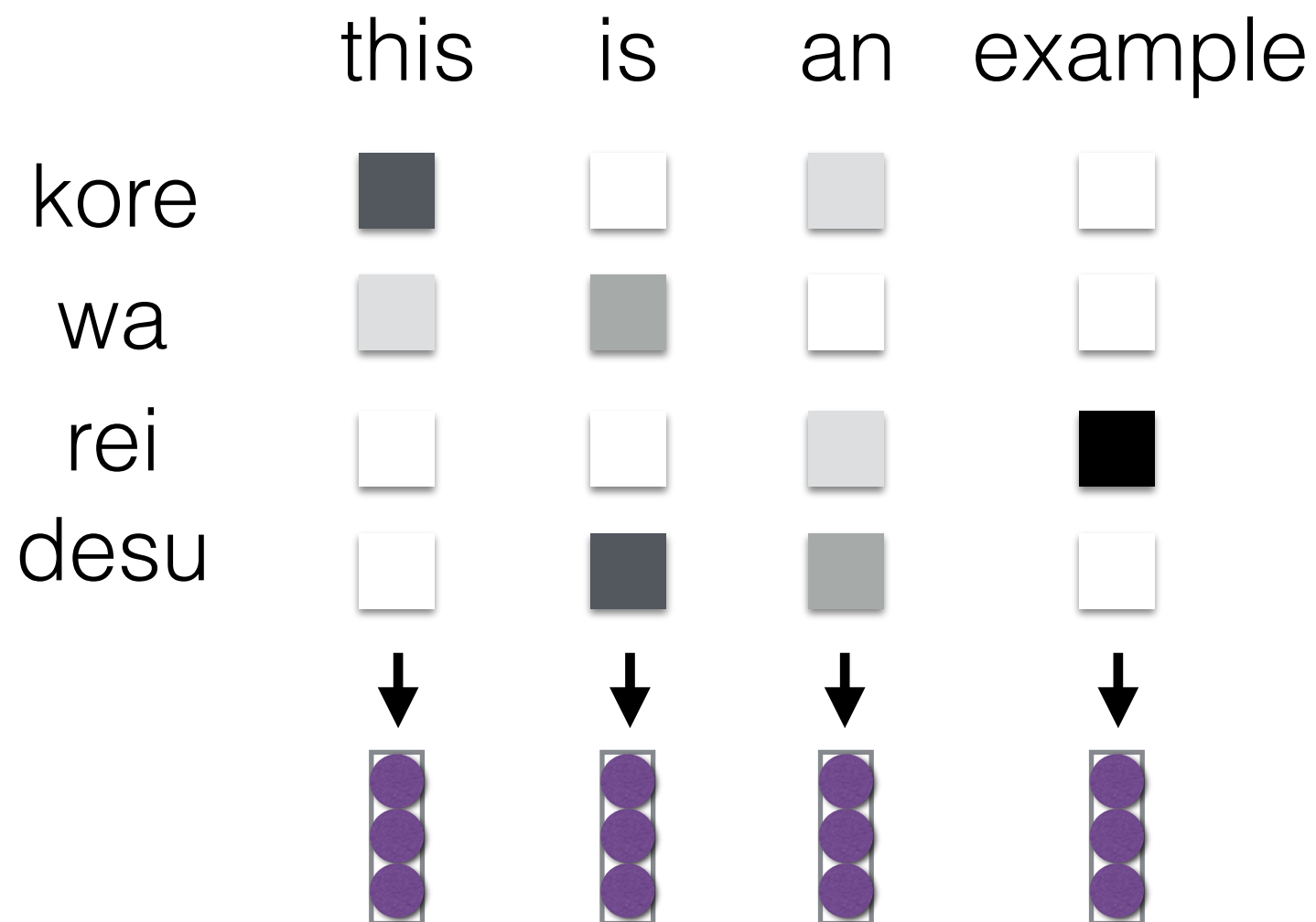
(Bahdanau et al. 2015)

- Encode each token in the sequence into a vector
- When decoding, perform a linear combination of these vectors, weighted by “attention weights”

Cross Attention

(Bahdanau et al. 2015)

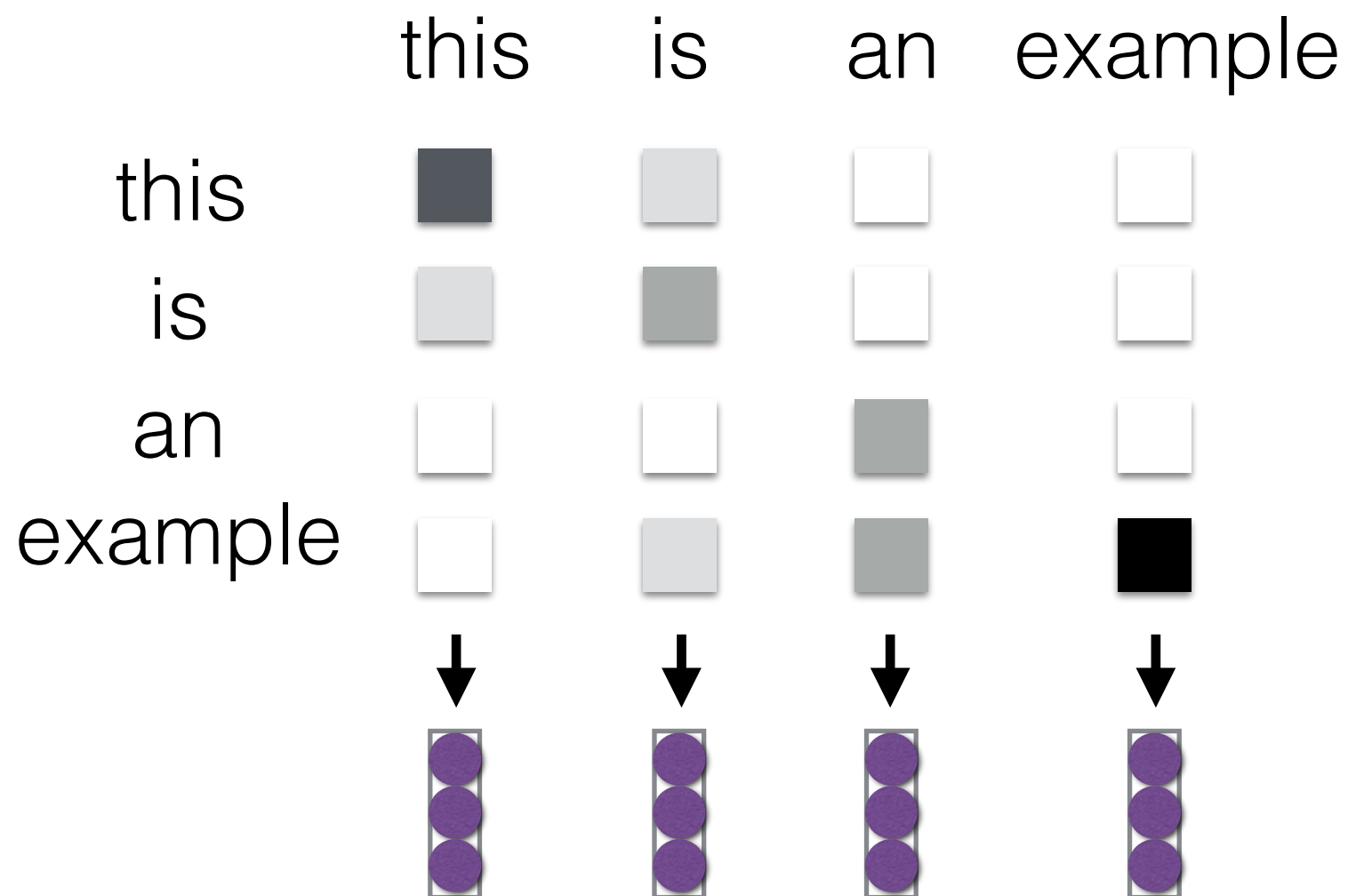
- Each element in a sequence attends to elements of another sequence



Self Attention

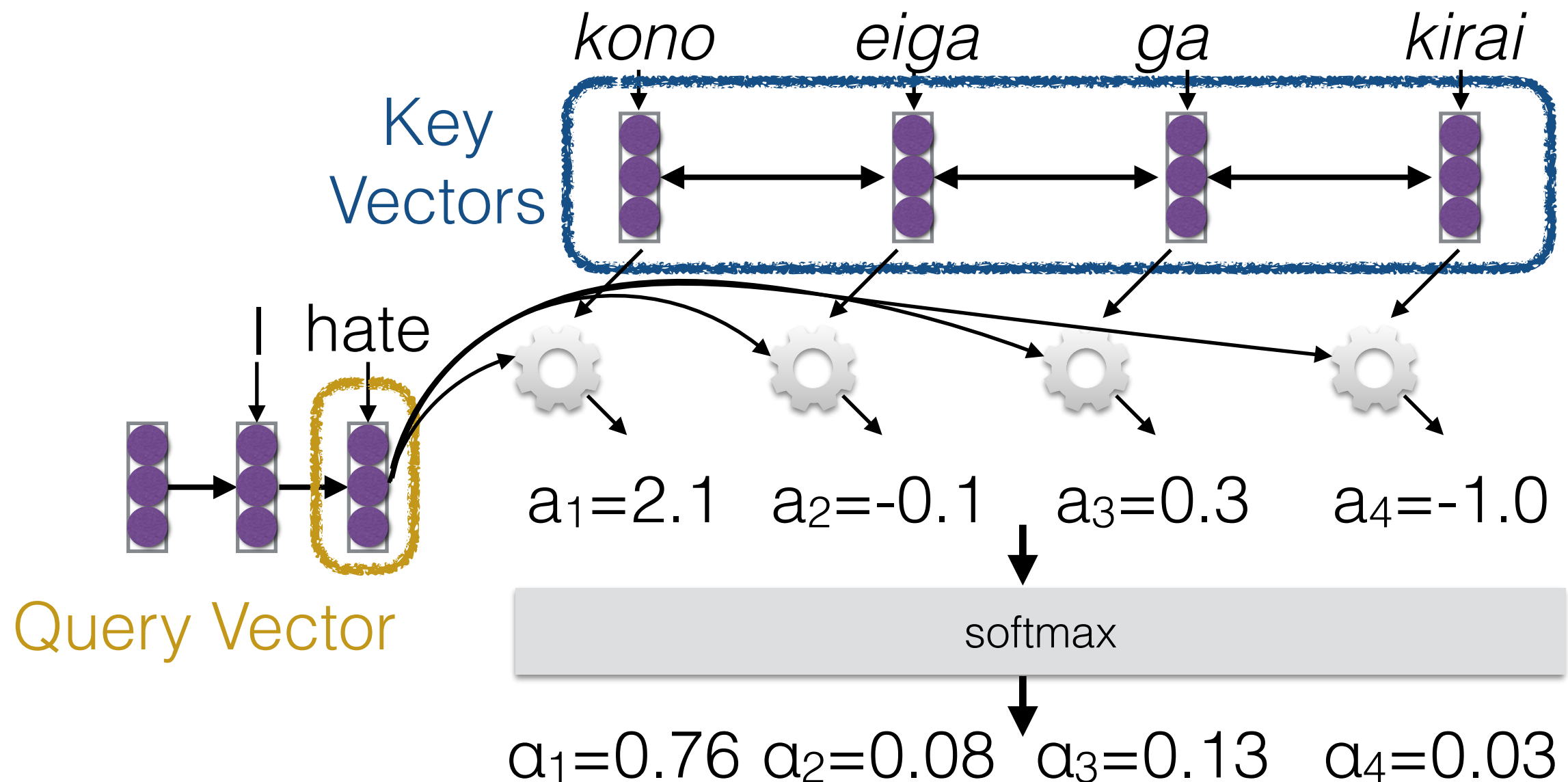
(Cheng et al. 2016, Vaswani et al. 2017)

- Each element in the sequence attends to elements of that sequence → context sensitive encodings!



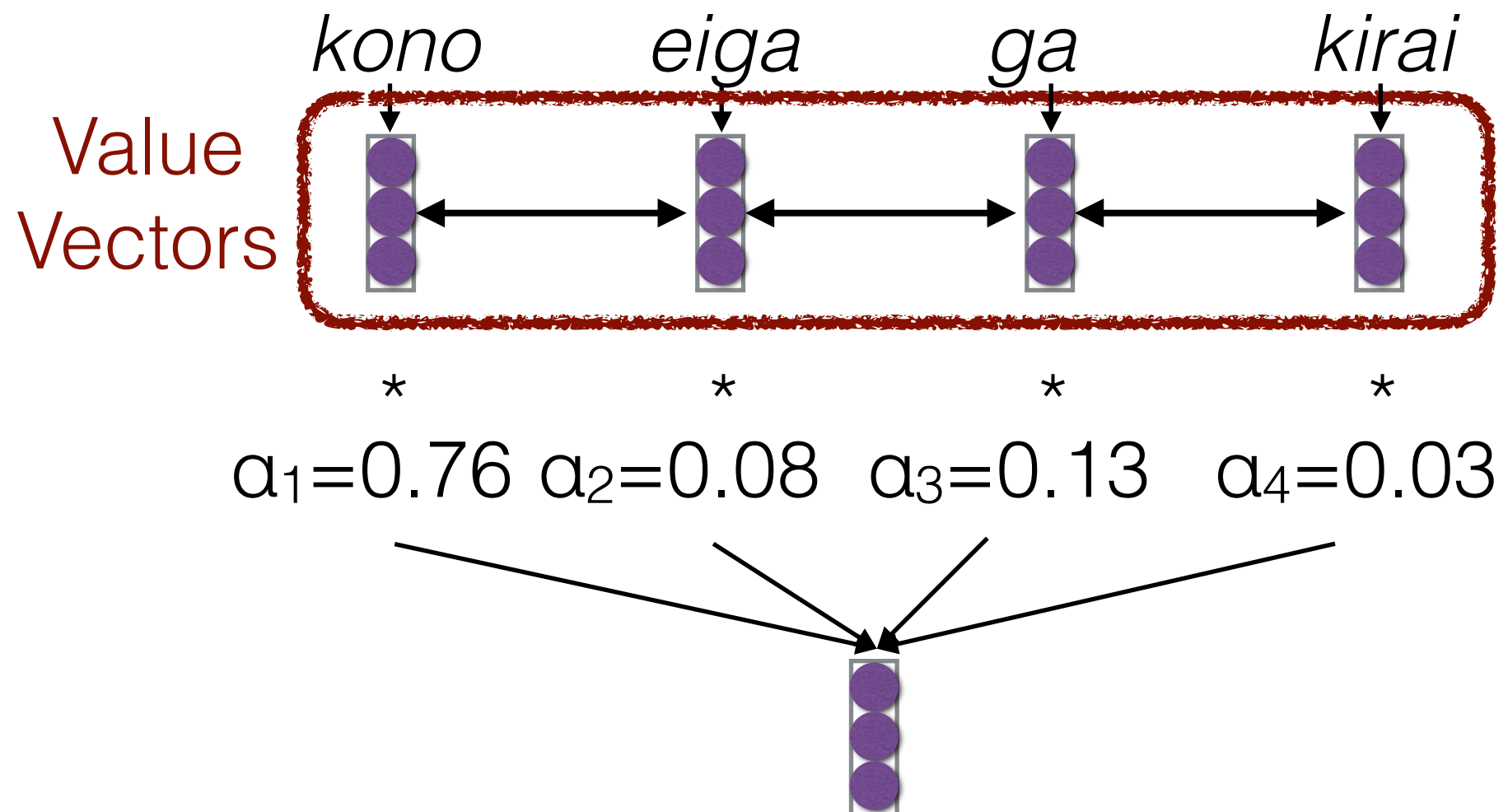
Calculating Attention (1)

- Use “query” vector (decoder state) and “key” vectors (all encoder states)
- For each query-key pair, calculate weight
- Normalize to add to one using softmax



Calculating Attention (2)

- Combine together value vectors (usually encoder states, like key vectors) by taking the weighted sum



- Use this in any part of the model you like

A Graphical Example

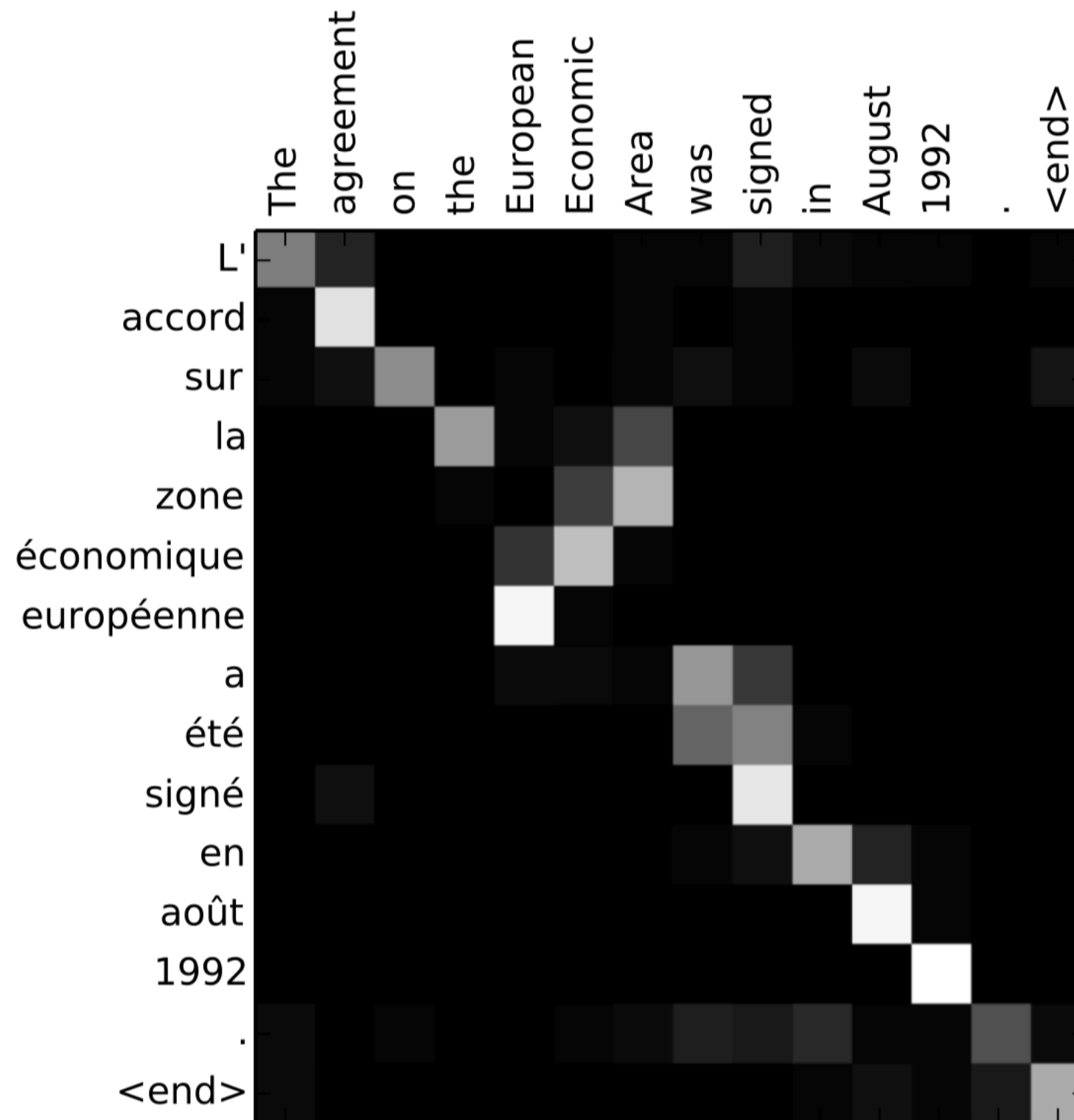


Image from Bahdanau et al. (2015)

Attention Score Functions (1)

- \mathbf{q} is the query and \mathbf{k} is the key
- **Multi-layer Perceptron** (Bahdanau et al. 2015)

$$a(\mathbf{q}, \mathbf{k}) = \mathbf{w}_2^\top \tanh(W_1[\mathbf{q}; \mathbf{k}])$$

- Flexible, often very good with large data
- **Bilinear** (Luong et al. 2015)

$$a(\mathbf{q}, \mathbf{k}) = \mathbf{q}^\top W \mathbf{k}$$

Attention Score Functions (2)

- **Dot Product** (Luong et al. 2015)

$$a(\mathbf{q}, \mathbf{k}) = \mathbf{q}^\top \mathbf{k}$$

- No parameters! But requires sizes to be the same.

- **Scaled Dot Product** (Vaswani et al. 2017)

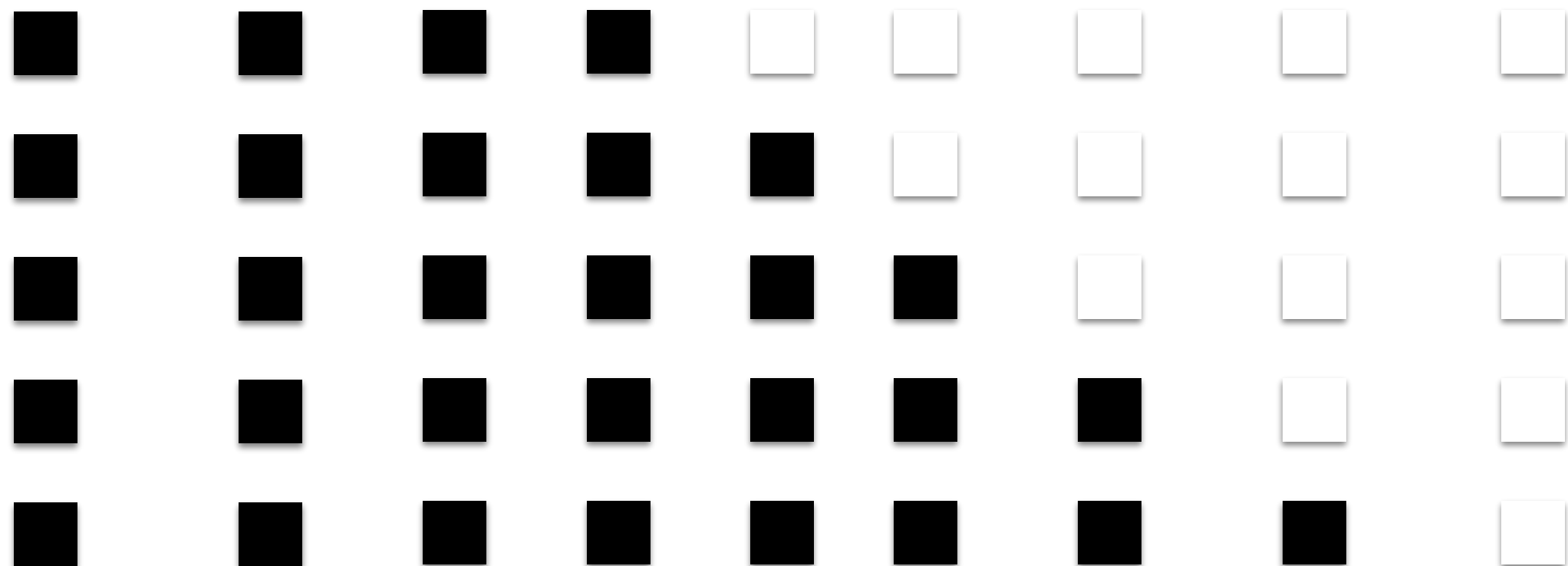
- *Problem*: scale of dot product increases as dimensions get larger
- *Fix*: scale by size of the vector

$$a(\mathbf{q}, \mathbf{k}) = \frac{\mathbf{q}^\top \mathbf{k}}{\sqrt{|\mathbf{k}|}}$$

Masking for Training

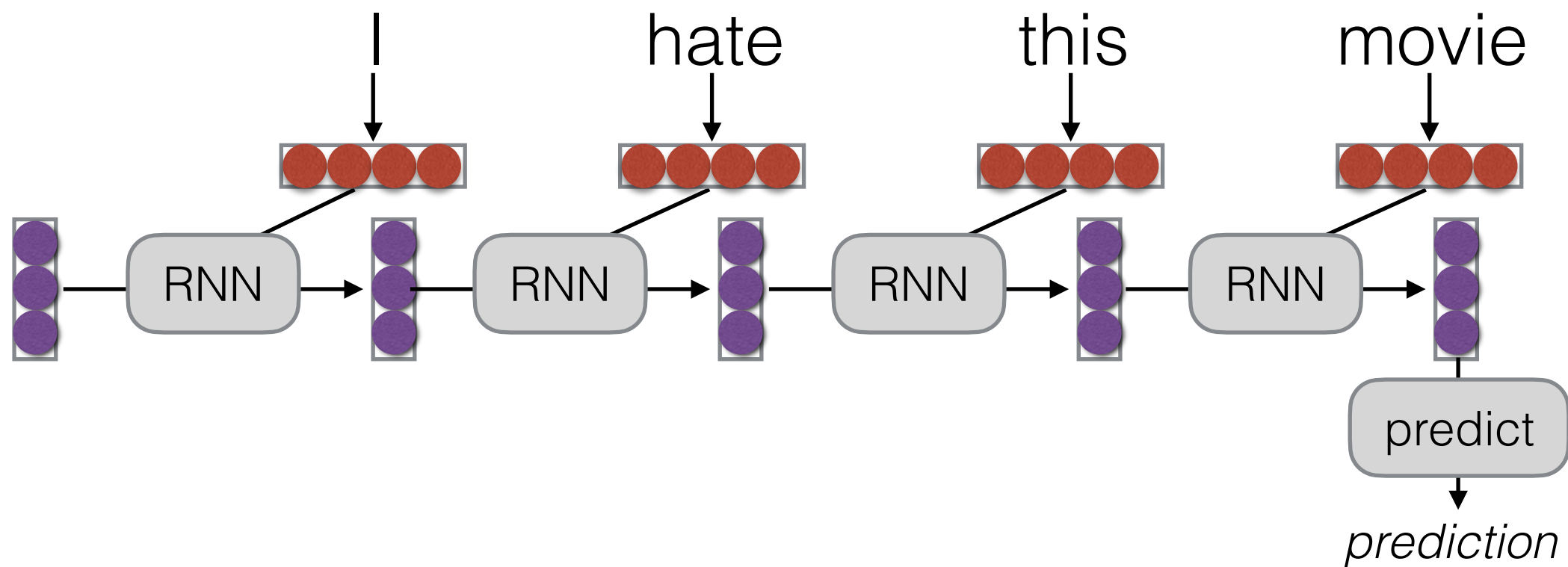
- We want to perform training in as few operations as possible using big matrix multiplies
- We can do so by “masking” the results for the output

kono eiga ga kirai I hate this movie </s>



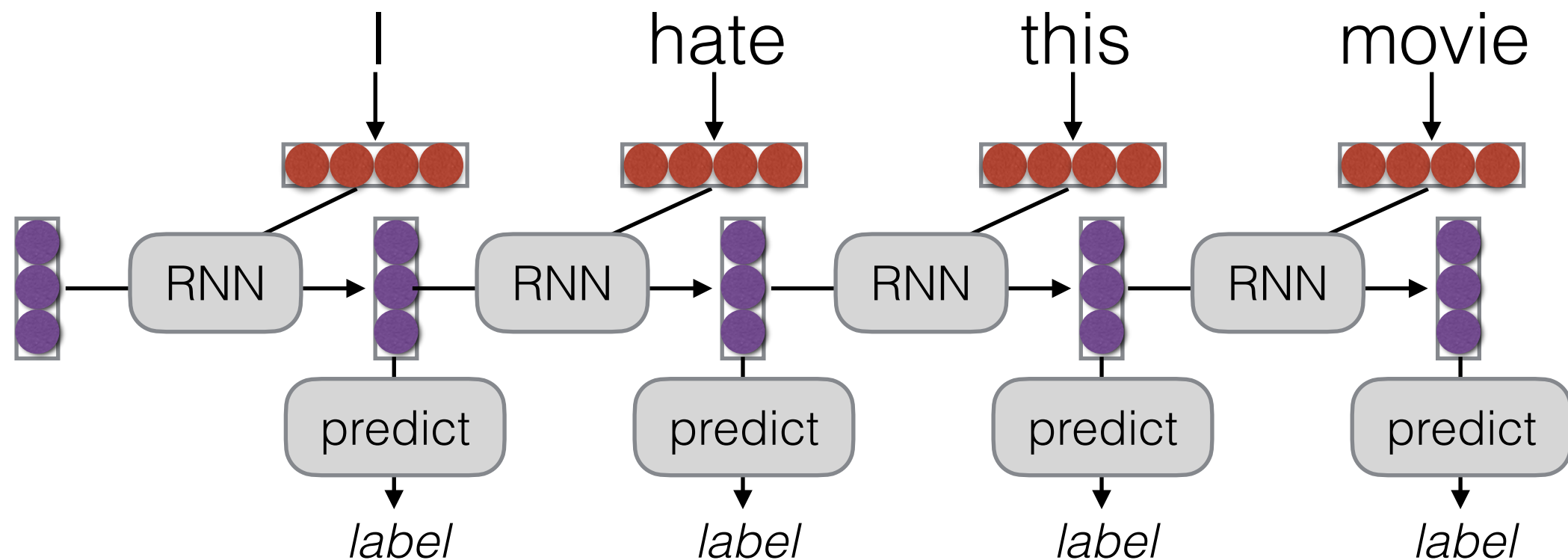
Applications of Sequence Models

Encoding Sequences



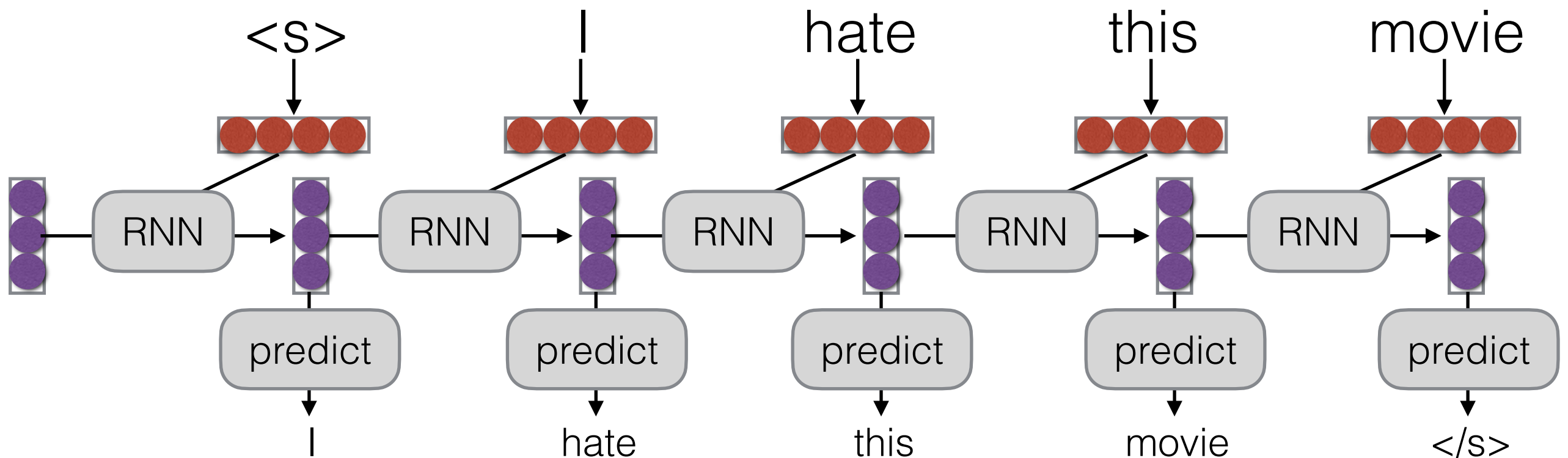
- Binary or multi-class prediction
- Sentence representation for retrieval, sentence comparison, etc.

Encoding Tokens



- Sequence labeling
- Language Modeling

e.g. Language Modeling



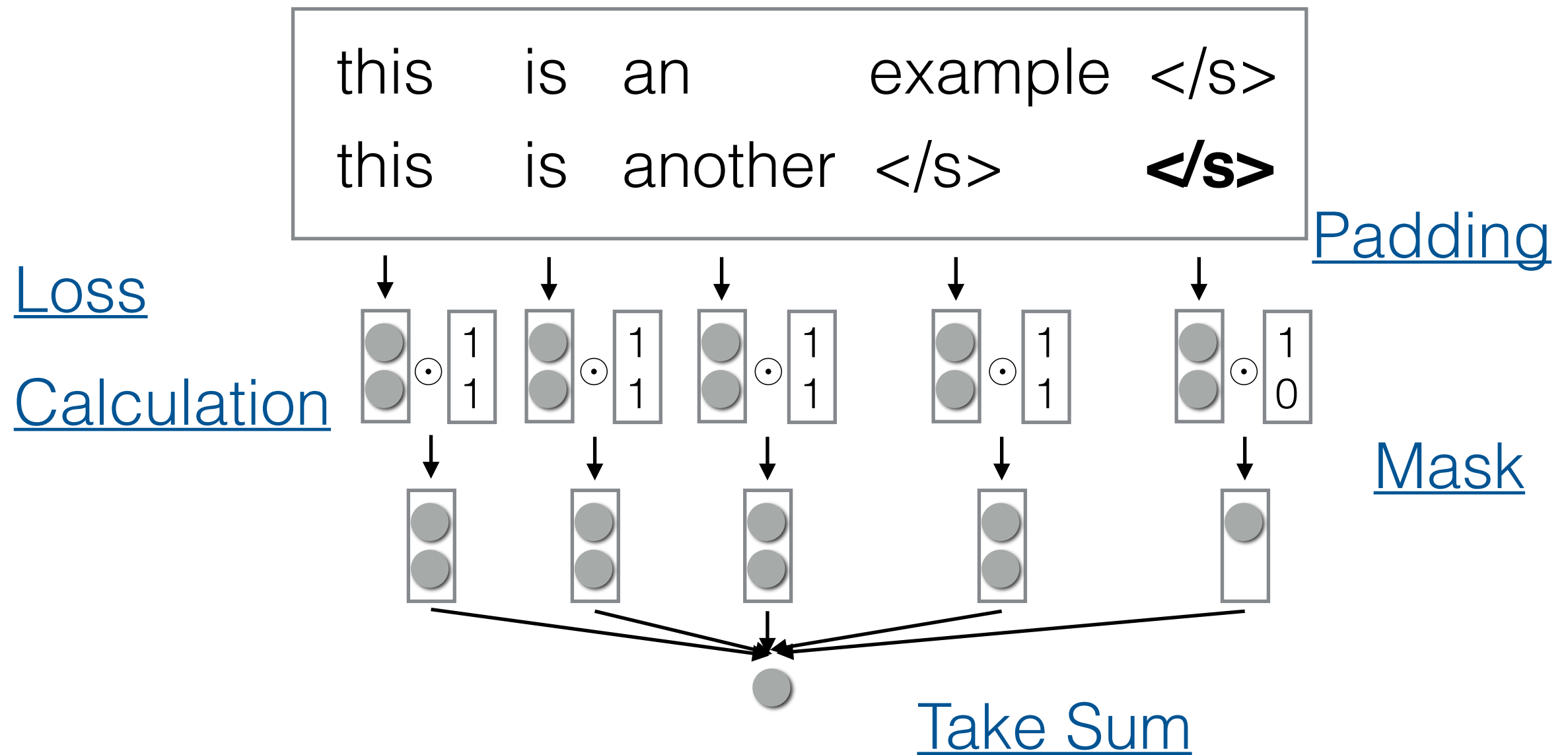
- Language modeling is like a tagging task, where each tag is the next word!
- Note: this is an autoregressive model

Efficiency Tricks for Sequence Modeling

Handling Mini-batching

- Mini-batching makes things much faster!
- But mini-batching in sequence modeling is harder than in feed-forward networks
 - Each word depends on the previous word
 - Sequences are of various length

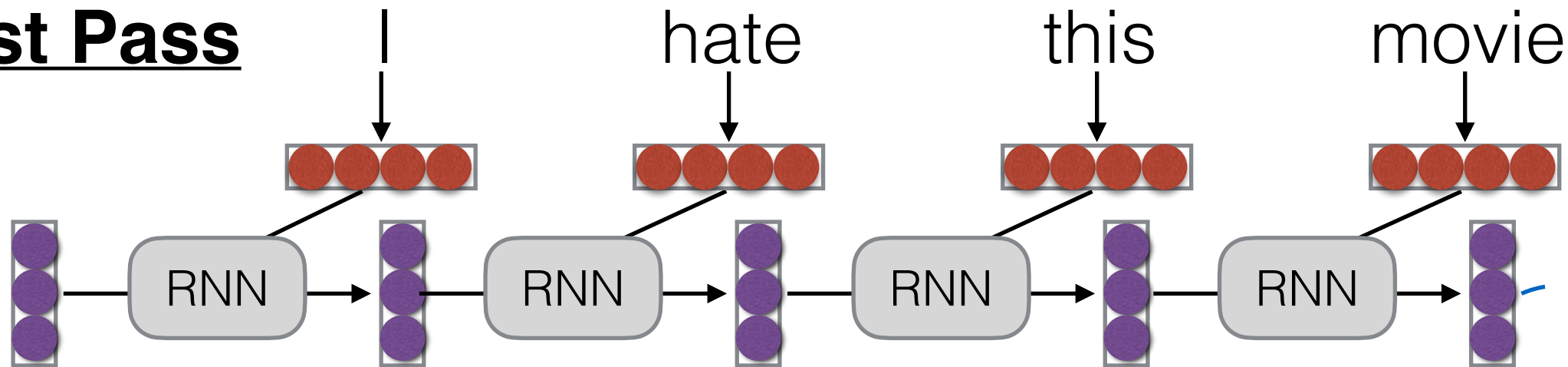
Mini-batching Method



Truncated BPTT

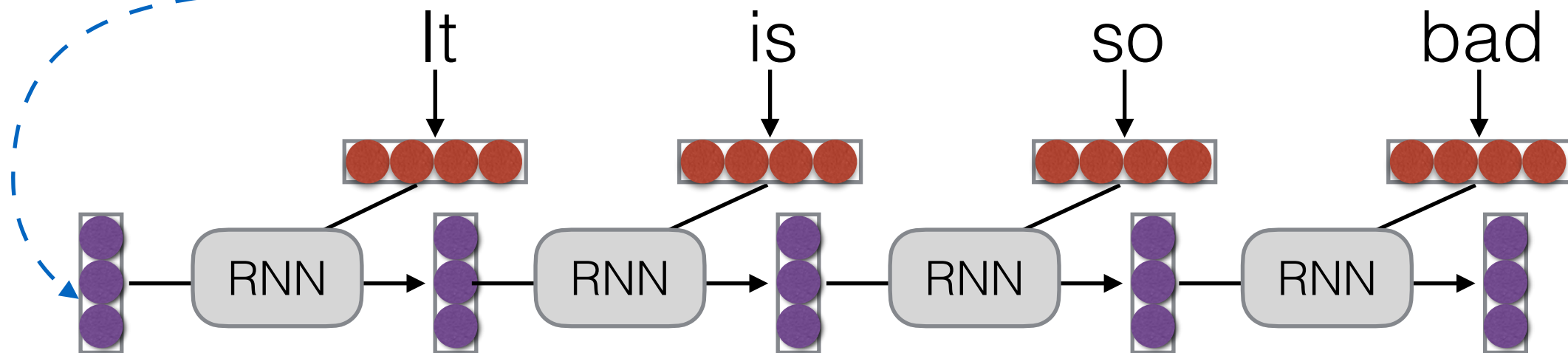
- Backprop over shorter segments, initialize w/ the state from the previous segment

1st Pass



2nd Pass

state only, no backprop



Questions?