

Natural Language Processing with Deep Learning

CS224N/Ling284



Lecture 8:
Recurrent Neural Networks
and Language Models

Abigail See

Announcements

- Assignment 1: Grades will be released after class
- Assignment 2: Coding session next week on Monday; details on Piazza
- Midterm logistics: Fill out form on Piazza if you can't do main midterm, have special requirements, or other special case

Announcements

- Default Final Project (PA4) release late tonight
 - Read the handout, look at the code, decide which project you want to do
 - You may not understand all the technical parts, but you'll get an overview
 - You don't yet have the Azure resources you need to run the code
- Project proposal due next week (Thurs Feb 8)
 - Details released later today
 - Everyone submits their teams
 - Custom final project teams also describe their project

Call for participation



APPLY TO BE A
MENTOR BY 2/18

ONE DAY WORKSHOP
TEACH WHAT YOU KNOW AND LOVE
MINIMUM CO-REQUISITE: CS106A

APPLY HERE: [HTTP://BIT.LY/GTGTMENTOR2018](http://bit.ly/GTGTMENTOR2018)

Overview

Today we will:

- Introduce a new NLP task
 - **Language Modeling**



motivates

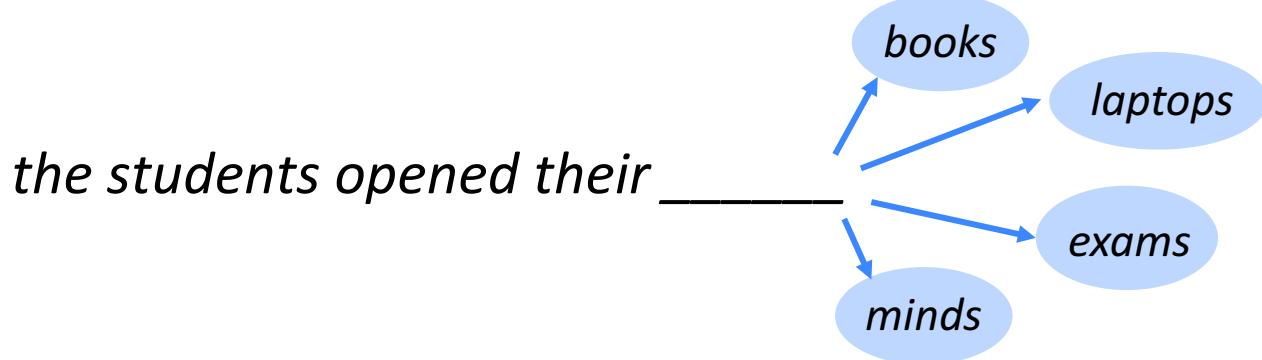
- Introduce a new family of neural networks
 - **Recurrent Neural Networks (RNNs)**



THE most important idea
for the rest of the class!

Language Modeling

- **Language Modeling** is the task of predicting what word comes next.



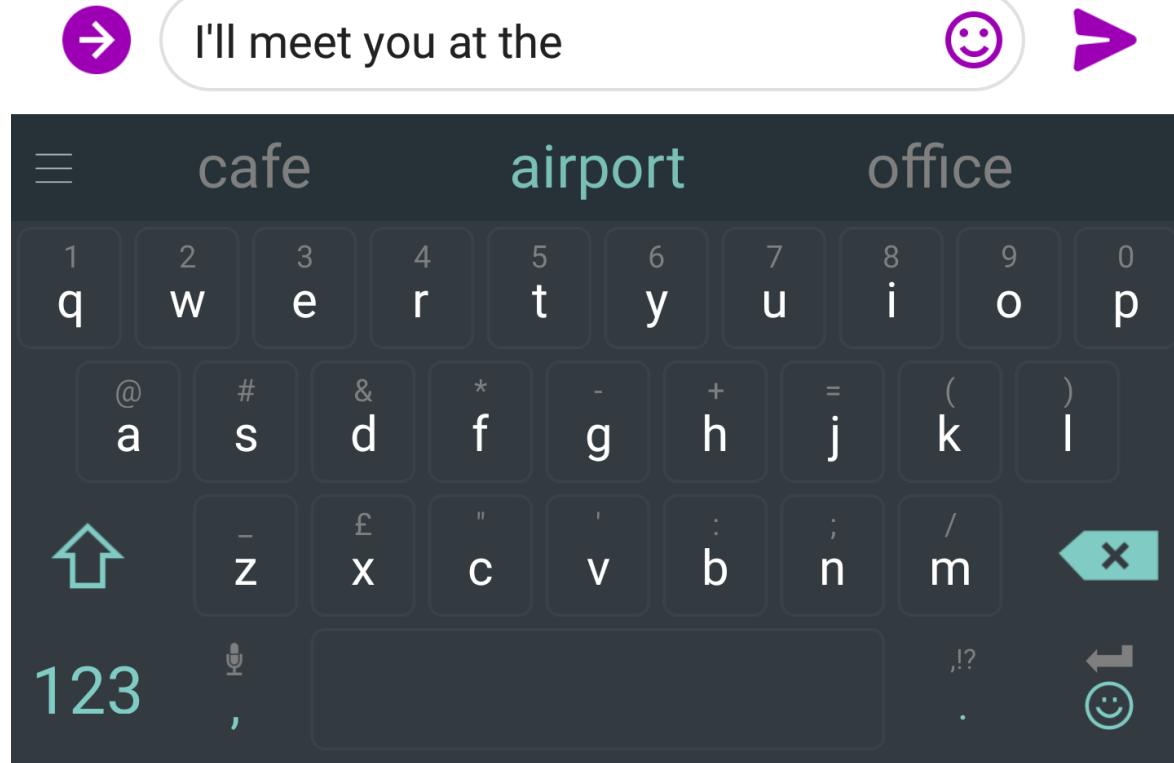
- More formally: given a sequence of words $\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \dots, \mathbf{x}^{(t)}$, compute the probability distribution of the next word $\mathbf{x}^{(t+1)}$:

$$P(\mathbf{x}^{(t+1)} = \mathbf{w}_j \mid \mathbf{x}^{(t)}, \dots, \mathbf{x}^{(1)})$$

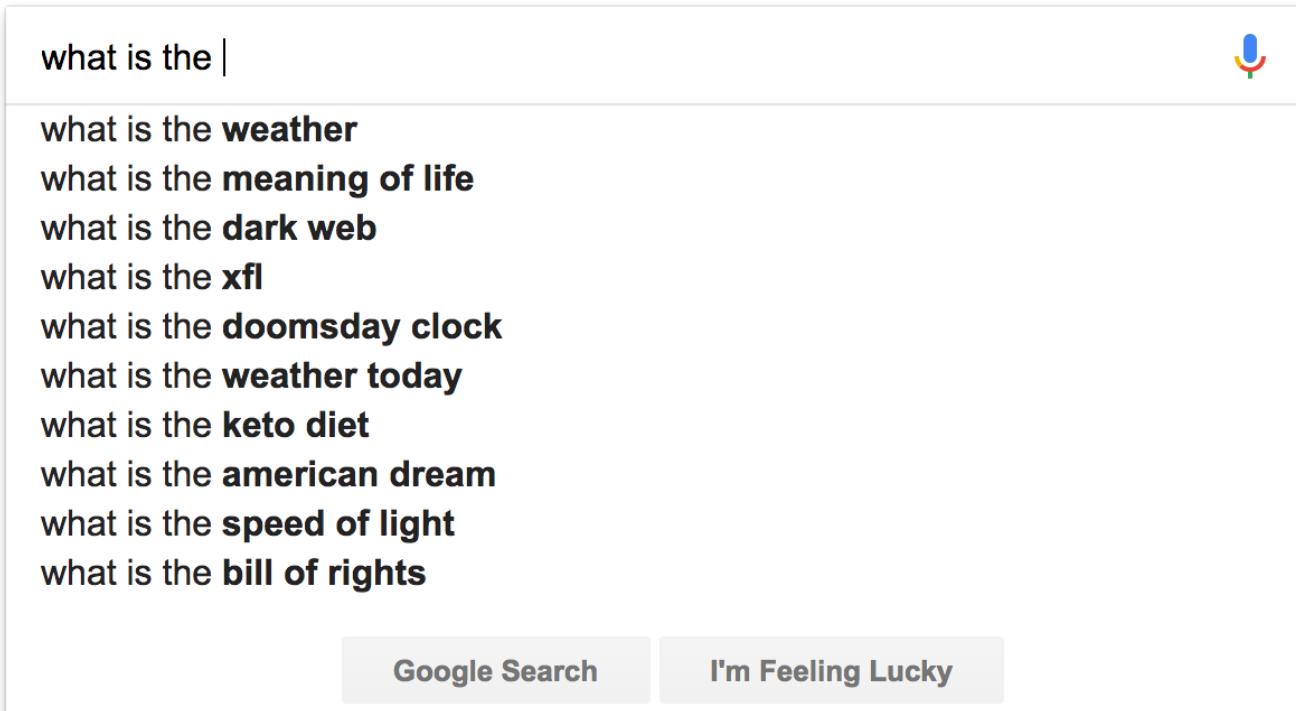
where \mathbf{w}_j is a word in the vocabulary $V = \{\mathbf{w}_1, \dots, \mathbf{w}_{|V|}\}$

- A system that does this is called a **Language Model**.

You use Language Models every day!



You use Language Models every day!

The Google logo is displayed in its signature multi-colored font: blue, red, yellow, and green.A screenshot of a Google search interface. The search bar at the top contains the text "what is the |". To the right of the search bar is a microphone icon. Below the search bar, a list of suggested search queries is shown, each starting with "what is the" followed by a bolded term. At the bottom of the interface are two buttons: "Google Search" and "I'm Feeling Lucky".

what is the |

what is the **weather**

what is the **meaning of life**

what is the **dark web**

what is the **xfl**

what is the **doomsday clock**

what is the **weather today**

what is the **keto diet**

what is the **american dream**

what is the **speed of light**

what is the **bill of rights**

Google Search

I'm Feeling Lucky

n-gram Language Models

the students opened their _____

- **Question:** How to learn a Language Model?
- **Answer** (pre- Deep Learning): learn a *n-gram Language Model!*
- **Definition:** A *n-gram* is a chunk of *n* consecutive words.
 - **uni**grams: “the”, “students”, “opened”, “their”
 - **bi**grams: “the students”, “students opened”, “opened their”
 - **tri**grams: “the students opened”, “students opened their”
 - **4**-grams: “the students opened their”
- **Idea:** Collect statistics about how frequent different n-grams are, and use these to predict next word.

n-gram Language Models

- First we make a **simplifying assumption**: $\mathbf{x}^{(t+1)}$ depends only on the preceding $(n-1)$ words

$$P(\mathbf{x}^{(t+1)} | \mathbf{x}^{(t)}, \dots, \mathbf{x}^{(1)}) = P(\mathbf{x}^{(t+1)} | \underbrace{\mathbf{x}^{(t)}, \dots, \mathbf{x}^{(t-n+2)}}_{n-1 \text{ words}}) \quad (\text{assumption})$$

$$\begin{aligned} \text{prob of a n-gram} &\rightarrow P(\mathbf{x}^{(t+1)}, \mathbf{x}^{(t)}, \dots, \mathbf{x}^{(t-n+2)}) \\ \text{prob of a (n-1)-gram} &= P(\mathbf{x}^{(t)}, \dots, \mathbf{x}^{(t-n+2)}) \end{aligned} \quad (\text{definition of conditional prob})$$

- Question:** How do we get these n -gram and $(n-1)$ -gram probabilities?
- Answer:** By **counting** them in some large corpus of text!

$$\approx \frac{\text{count}(\mathbf{x}^{(t+1)}, \mathbf{x}^{(t)}, \dots, \mathbf{x}^{(t-n+2)})}{\text{count}(\mathbf{x}^{(t)}, \dots, \mathbf{x}^{(t-n+2)})} \quad (\text{statistical approximation})$$

n-gram Language Models: Example

Suppose we are learning a **4-gram** Language Model.

~~as the proctor started the clock, the~~ students opened their _____
discard _____
condition on this _____

$$P(\mathbf{w}_j | \text{students opened their}) = \frac{\text{count(students opened their } \mathbf{w}_j\text{)}}{\text{count(students opened their)}}$$

In the corpus:

- “students opened their” occurred 1000 times
 - “students opened their books” occurred 400 times
 - $\rightarrow P(\text{books} \mid \text{students opened their}) = 0.4$
 - “students opened their exams” occurred 100 times
 - $\rightarrow P(\text{exams} \mid \text{students opened their}) = 0.1$

Should we have
discarded the
“proctor” context?

Problems with n-gram Language Models

Sparsity Problem 1

Problem: What if “*students opened their w_j* ” never occurred in data? Then w_j has probability 0!

(Partial) Solution: Add small δ to count for every $w_j \in V$. This is called *smoothing*.

$$P(w_j | \text{students opened their}) = \frac{\text{count}(\text{students opened their } w_j)}{\text{count}(\text{students opened their})}$$

Sparsity Problem 2

Problem: What if “*students opened their*” never occurred in data? Then we can’t calculate probability for *any* w_j !

(Partial) Solution: Just condition on “*opened their*” instead. This is called *backoff*.

Note: Increasing n makes sparsity problems *worse*. Typically we can’t have n bigger than 5.

Problems with n-gram Language Models

Storage: Need to store count for all possible n -grams. So model size is $O(\exp(n))$.

$$P(w_j | \text{students opened their}) = \frac{\text{count(students opened their } w_j\text{)}}{\text{count(students opened their)}}$$

Increasing n makes model size huge!

n-gram Language Models in practice

- You can build a simple trigram Language Model over a 1.7 million word corpus (Reuters) in a few seconds on your laptop*

today the _____

Business and financial news

get probability distribution

company	0.153
bank	0.153
price	0.077
italian	0.039
emirate	0.039
...	

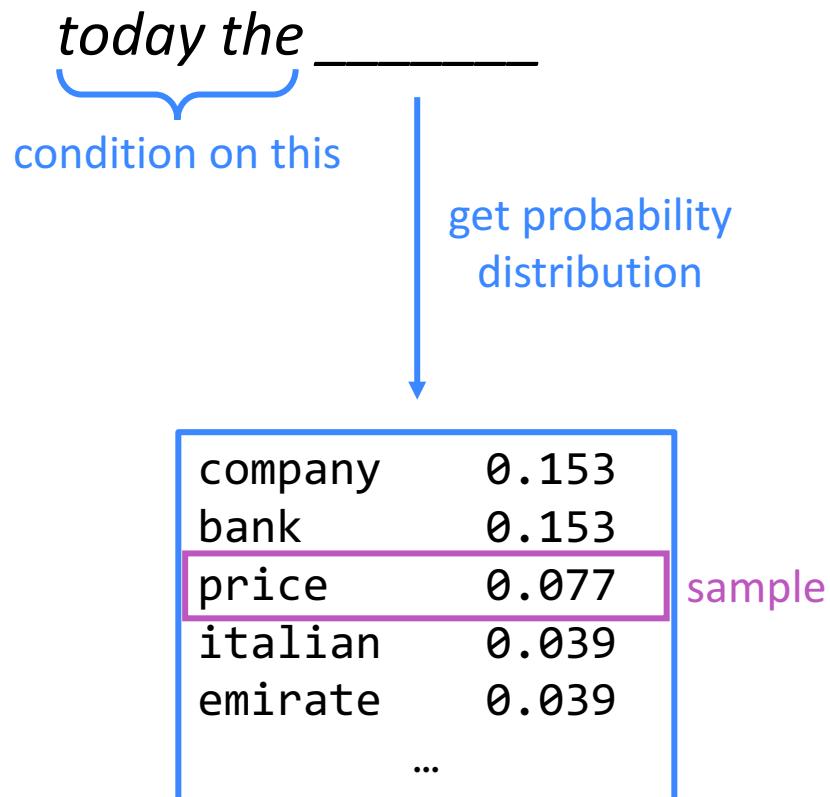
Sparsity problem:
not much granularity
in the probability
distribution

* Try for yourself: <https://nlpforhackers.io/language-models/>

Otherwise, seems reasonable!

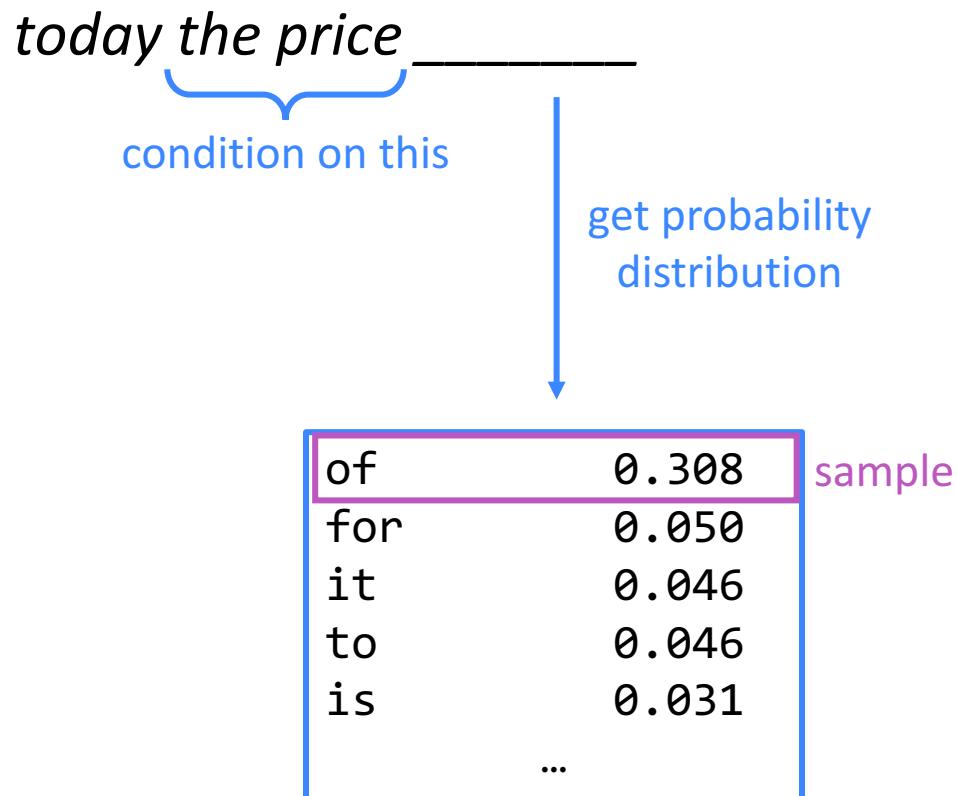
Generating text with a n-gram Language Model

- You can also use a Language Model to generate text.



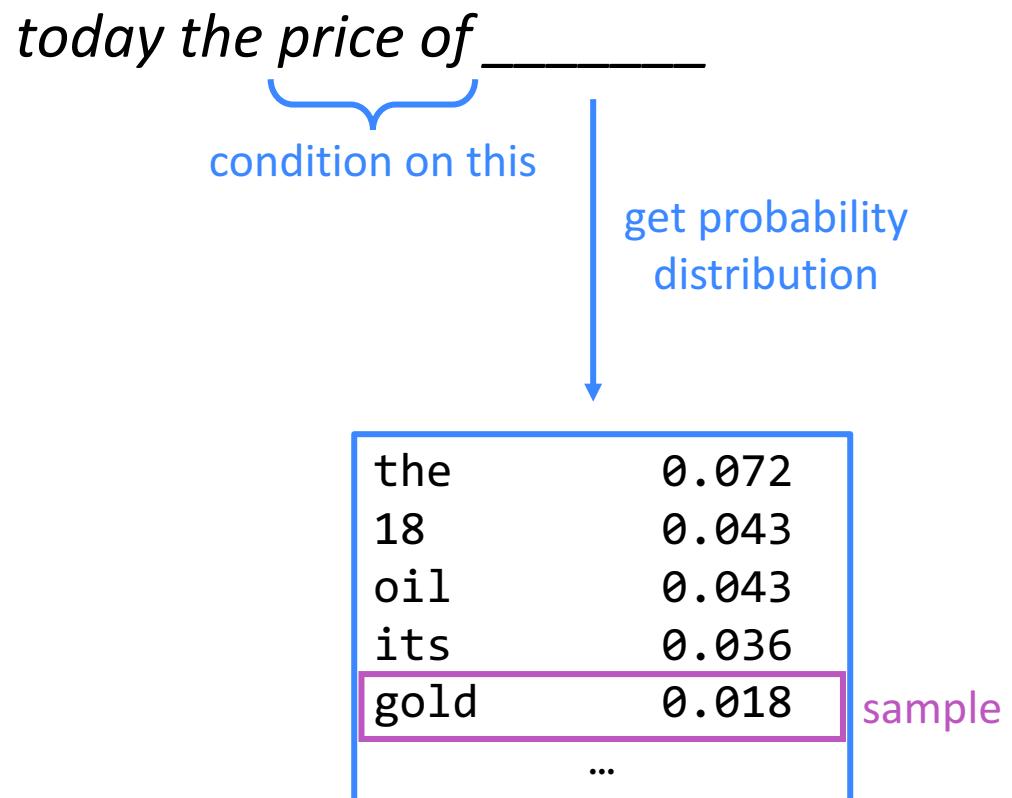
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Generating text with a n-gram Language Model

- You can also use a Language Model to generate text.



Generating text with a n-gram Language Model

- You can also use a Language Model to generate text.

today the price of gold _____

Generating text with a n-gram Language Model

- You can also use a Language Model to generate text.

today the price of gold per ton , while production of shoe lasts and shoe industry , the bank intervened just after it considered and rejected an imf demand to rebuild depleted european stocks , sept 30 end primary 76 cts a share .

Incoherent! We need to consider more than 3 words at a time if we want to generate good text.

But increasing n worsens sparsity problem, and exponentially increases model size...

How to build a *neural* Language Model?

- Recall the Language Modeling task:
 - Input: sequence of words $x^{(1)}, x^{(2)}, \dots, x^{(t)}$
 - Output: prob dist of the next word $P(x^{(t+1)} = w_j \mid x^{(t)}, \dots, x^{(1)})$
- How about a window-based neural model?
 - We saw this applied to Named Entity Recognition in Lecture 4

A fixed-window neural Language Model

as the proctor started the clock ~~the~~ students opened their _____

discard

fixed window

A fixed-window neural Language Model

output distribution

$$\hat{y} = \text{softmax}(\mathbf{U}\mathbf{h} + \mathbf{b}_2) \in \mathbb{R}^{|V|}$$

hidden layer

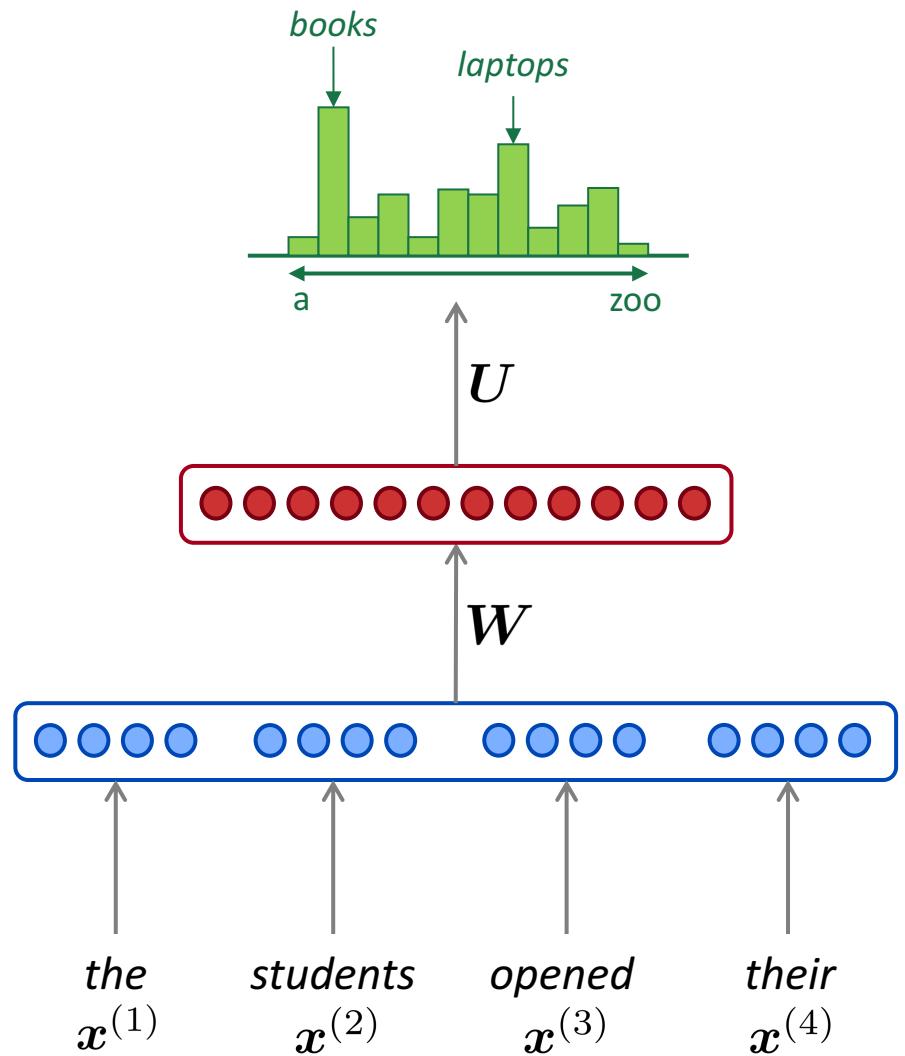
$$\mathbf{h} = f(\mathbf{W}\mathbf{e} + \mathbf{b}_1)$$

concatenated word embeddings

$$\mathbf{e} = [\mathbf{e}^{(1)}; \mathbf{e}^{(2)}; \mathbf{e}^{(3)}; \mathbf{e}^{(4)}]$$

words / one-hot vectors

$$\mathbf{x}^{(1)}, \mathbf{x}^{(2)}, \mathbf{x}^{(3)}, \mathbf{x}^{(4)}$$



A fixed-window neural Language Model

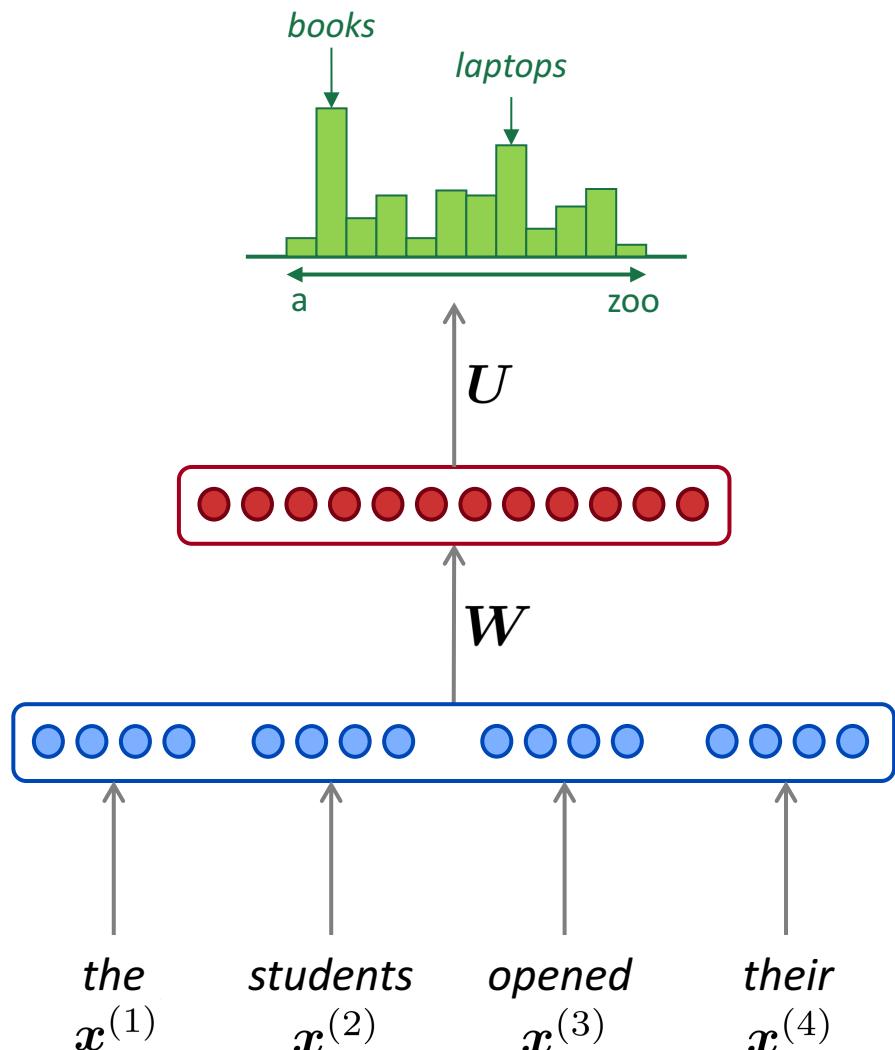
Improvements over n -gram LM:

- No sparsity problem
- Model size is $O(n)$ not $O(\exp(n))$

Remaining **problems**:

- Fixed window is **too small**
- Enlarging window enlarges W
- Window can never be large enough!
- Each $x^{(i)}$ uses different rows of W . We **don't share weights** across the window.

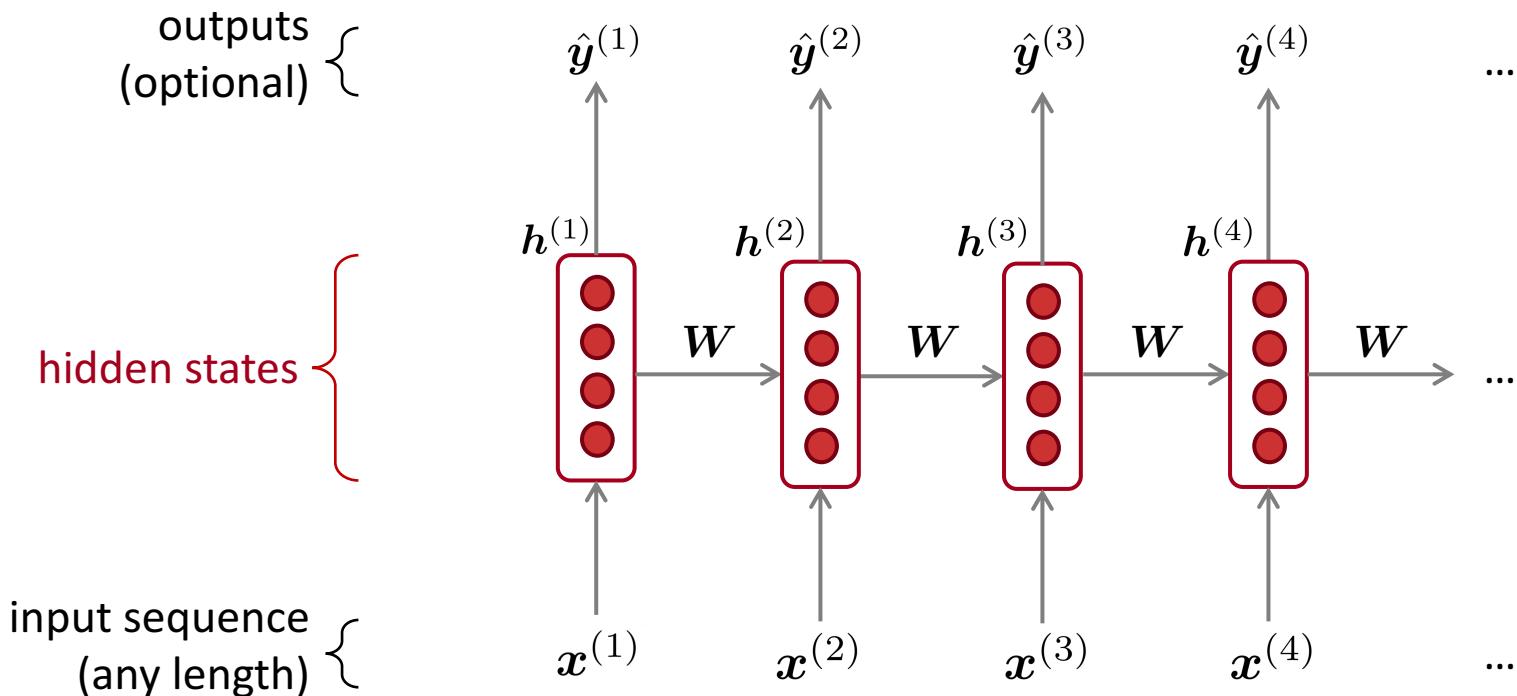
We need a neural architecture that can process *any length input*



Recurrent Neural Networks (RNN)

A family of neural architectures

Core idea: Apply the same weights W repeatedly

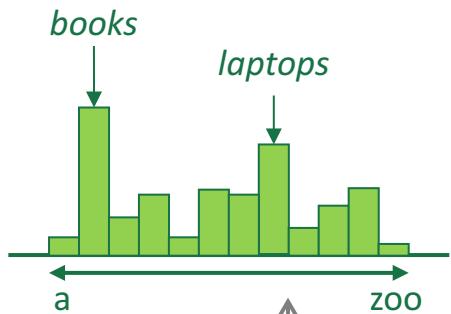


$$\hat{y}^{(4)} = P(x^{(5)} | \text{the students opened their})$$

A RNN Language Model

output distribution

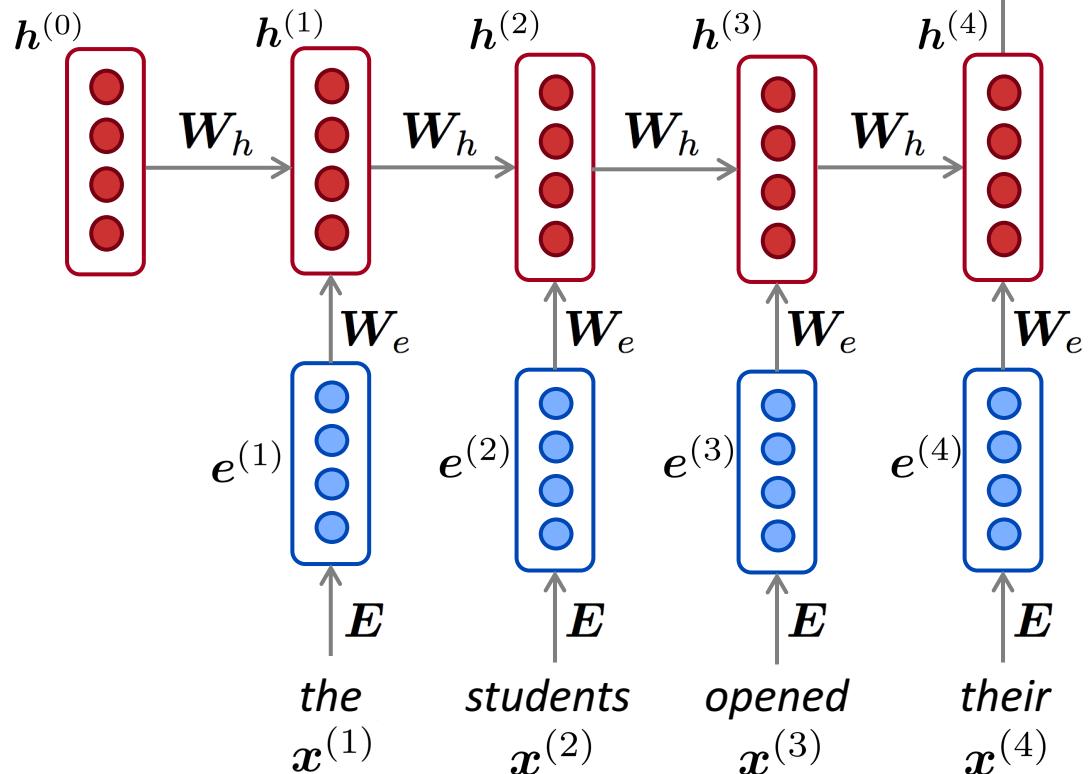
$$\hat{y}^{(t)} = \text{softmax}(\mathbf{U}\mathbf{h}^{(t)} + \mathbf{b}_2) \in \mathbb{R}^{|V|}$$



hidden states

$$\mathbf{h}^{(t)} = \sigma(\mathbf{W}_h \mathbf{h}^{(t-1)} + \mathbf{W}_e \mathbf{e}^{(t)} + \mathbf{b}_1)$$

$\mathbf{h}^{(0)}$ is the initial hidden state



word embeddings

$$\mathbf{e}^{(t)} = \mathbf{E}\mathbf{x}^{(t)}$$

words / one-hot vectors

$$\mathbf{x}^{(t)} \in \mathbb{R}^{|V|}$$

Note: this input sequence could be much longer, but this slide doesn't have space!

A RNN Language Model

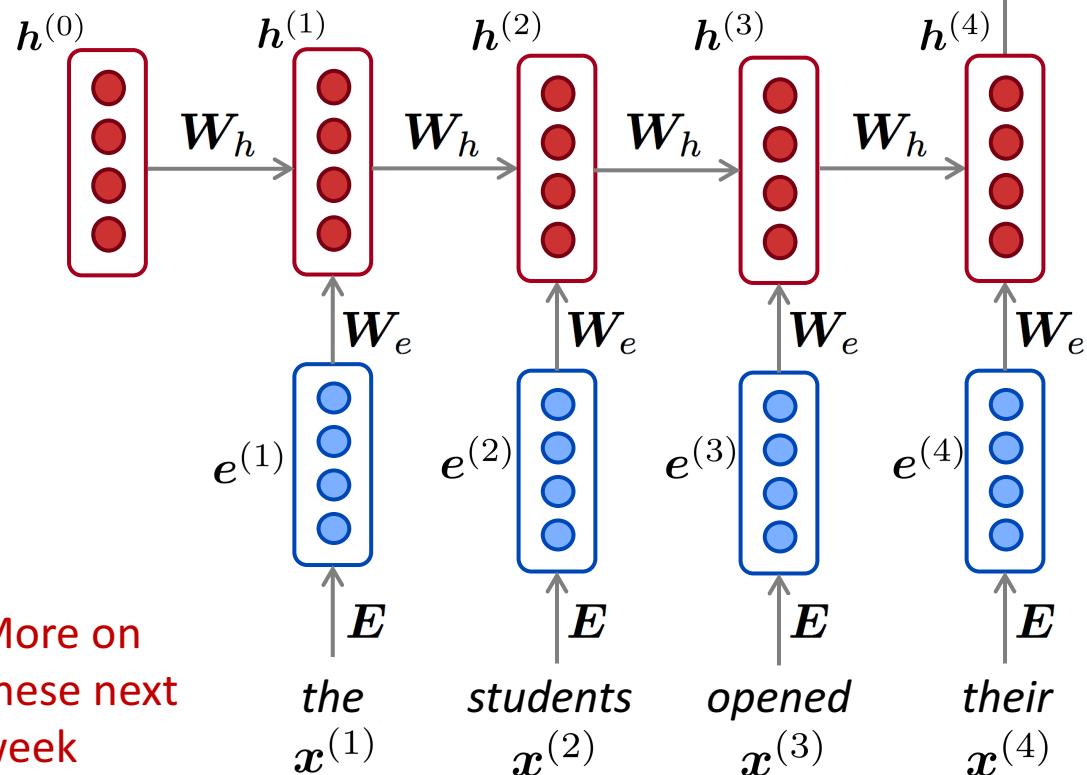
RNN Advantages:

- Can process **any length** input
- **Model size doesn't increase** for longer input
- Computation for step t can (in theory) use information from **many steps back**
- Weights are **shared** across timesteps \rightarrow representations are shared

RNN Disadvantages:

- Recurrent computation is **slow**
- In practice, difficult to access information from **many steps back**

More on these next week



Training a RNN Language Model

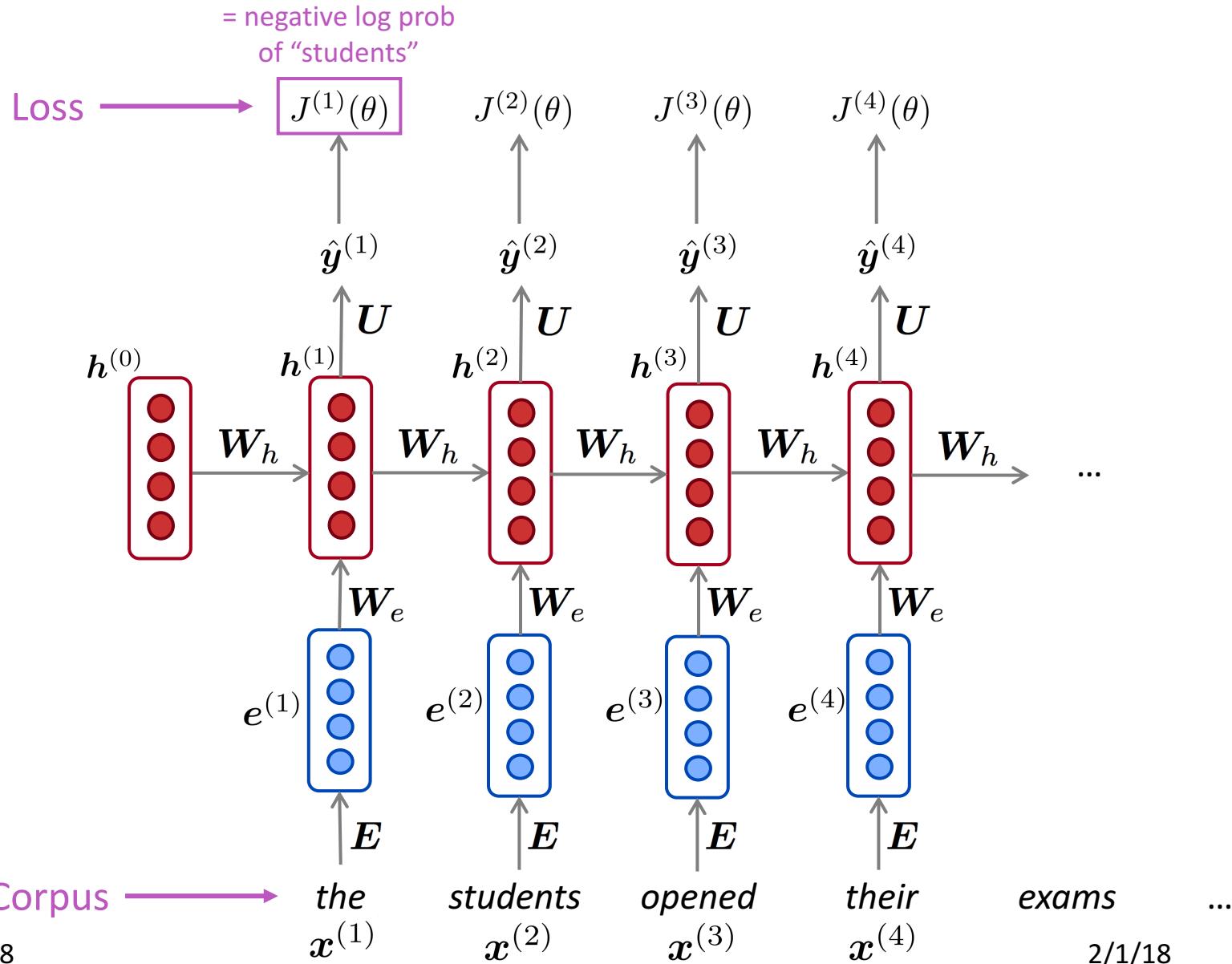
- Get a **big corpus of text** which is a sequence of words $\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(T)}$
- Feed into RNN-LM; compute output distribution $\hat{\mathbf{y}}^{(t)}$ **for every step t .**
 - i.e. predict probability dist of *every word*, given words so far
- **Loss function** on step t is usual cross-entropy between our predicted probability distribution $\hat{\mathbf{y}}^{(t)}$, and the true next word $\mathbf{y}^{(t)} = \mathbf{x}^{(t+1)}$:

$$J^{(t)}(\theta) = CE(\mathbf{y}^{(t)}, \hat{\mathbf{y}}^{(t)}) = - \sum_{j=1}^{|V|} y_j^{(t)} \log \hat{y}_j^{(t)}$$

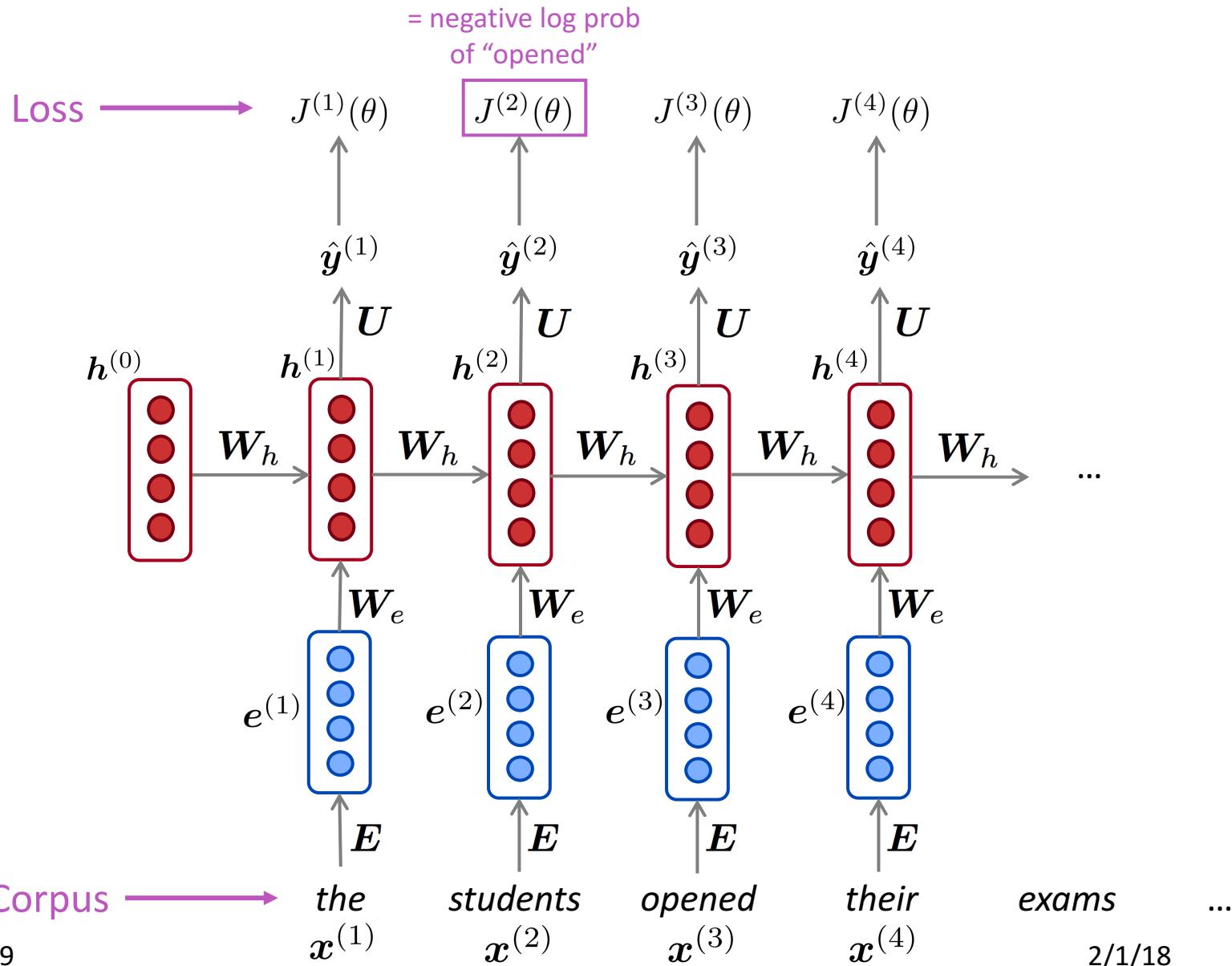
- Average this to get **overall loss** for entire training set:

$$J(\theta) = \frac{1}{T} \sum_{t=1}^T J^{(t)}(\theta)$$

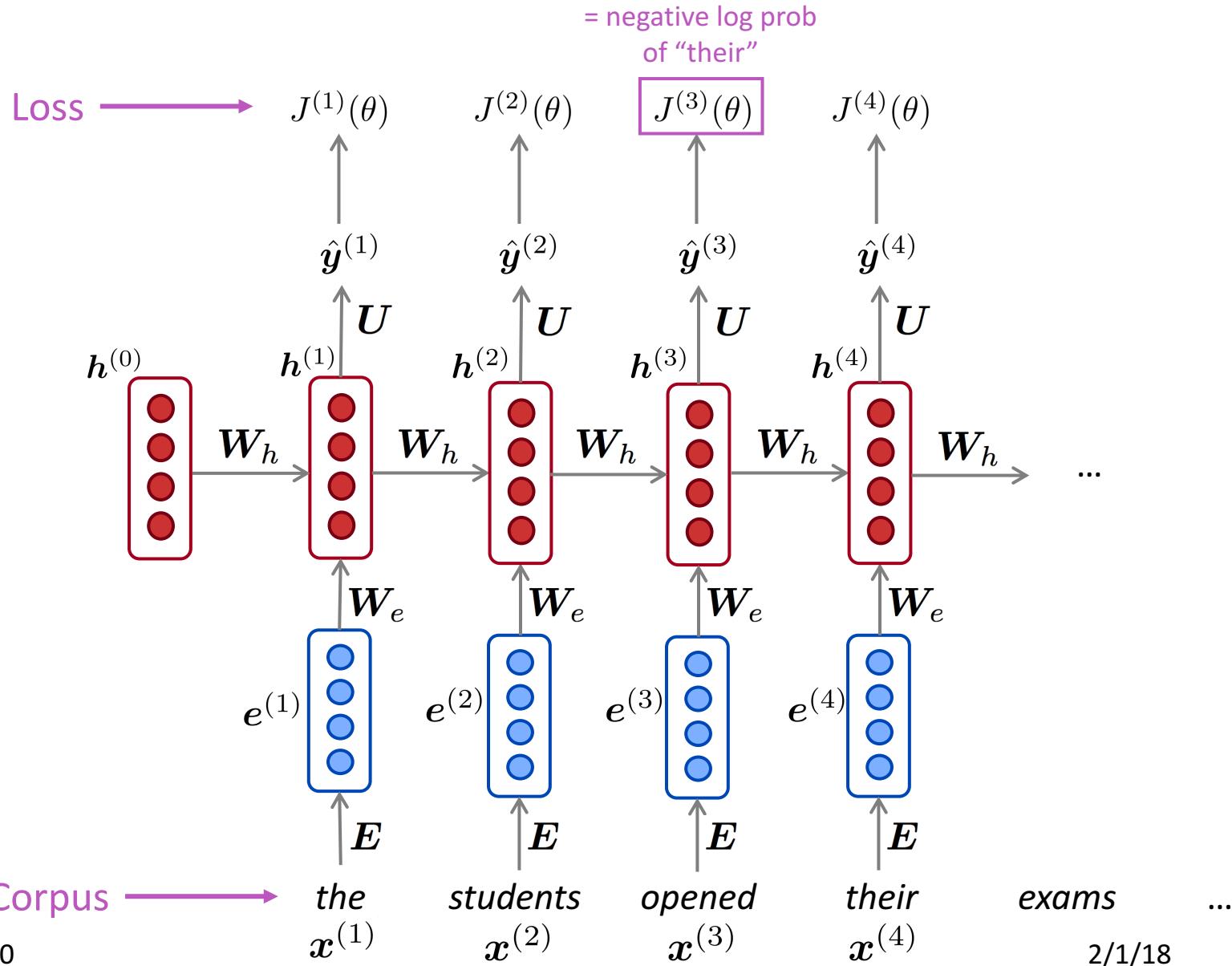
Training a RNN Language Model



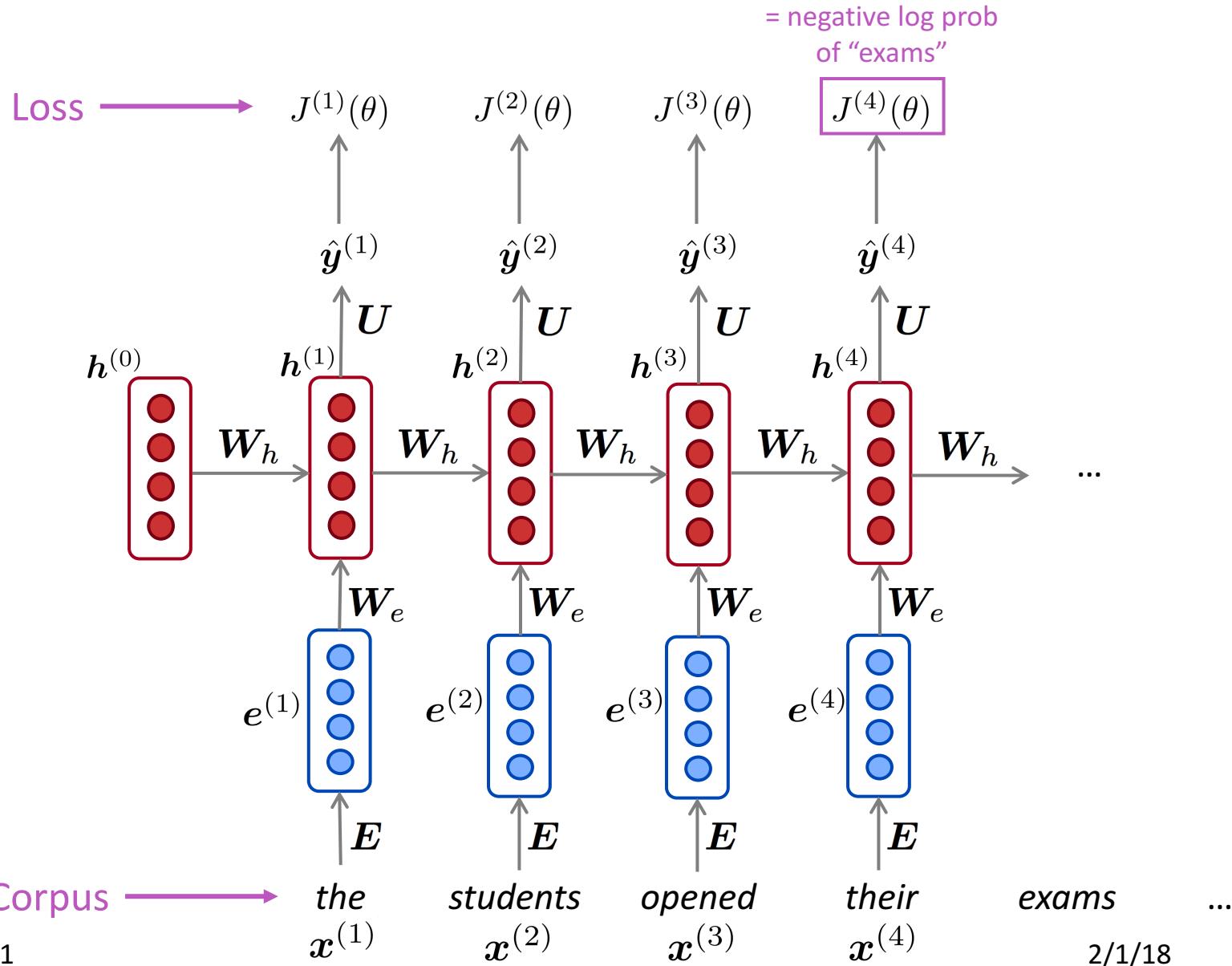
Training a RNN Language Model



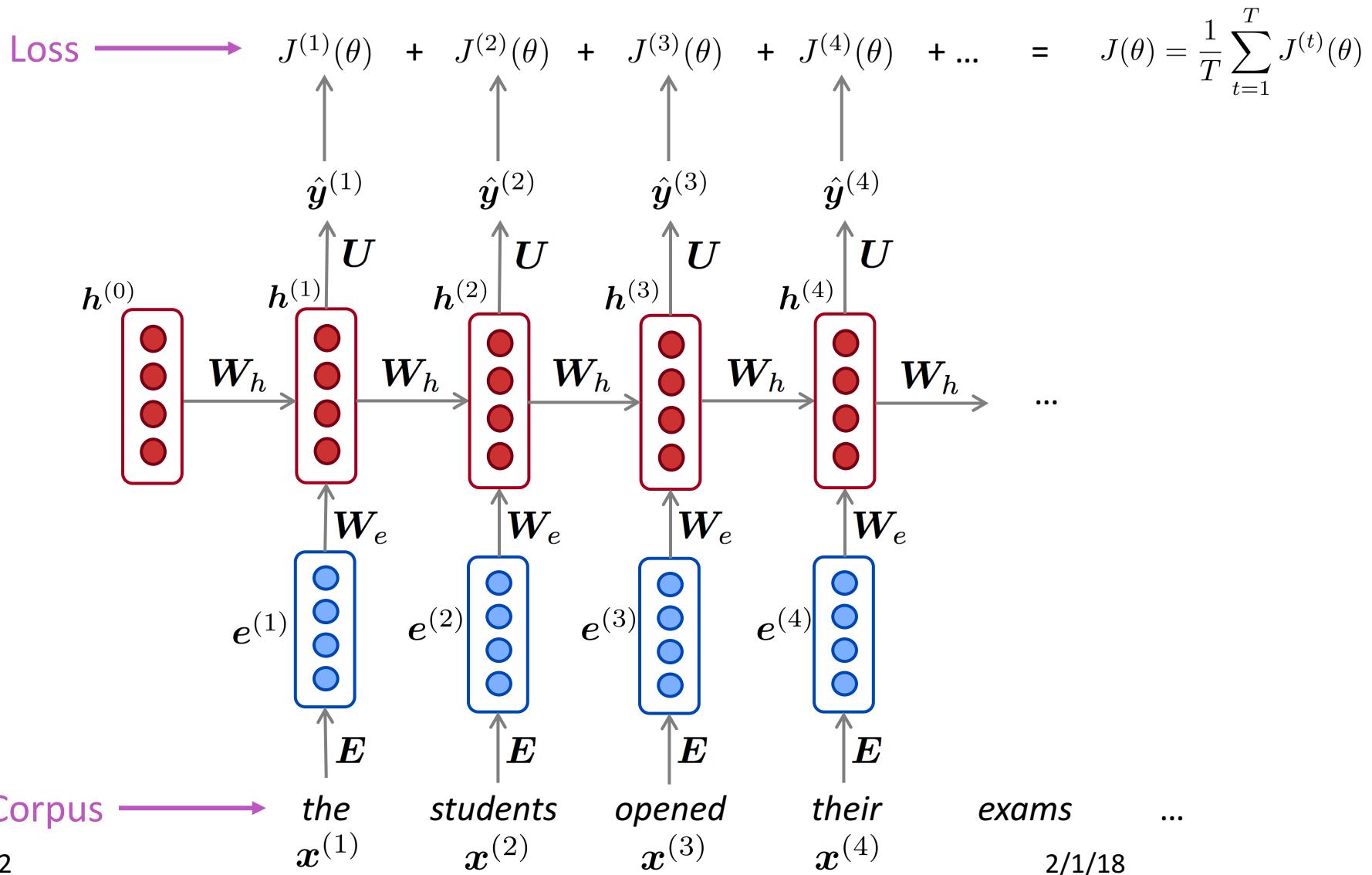
Training a RNN Language Model



Training a RNN Language Model



Training a RNN Language Model



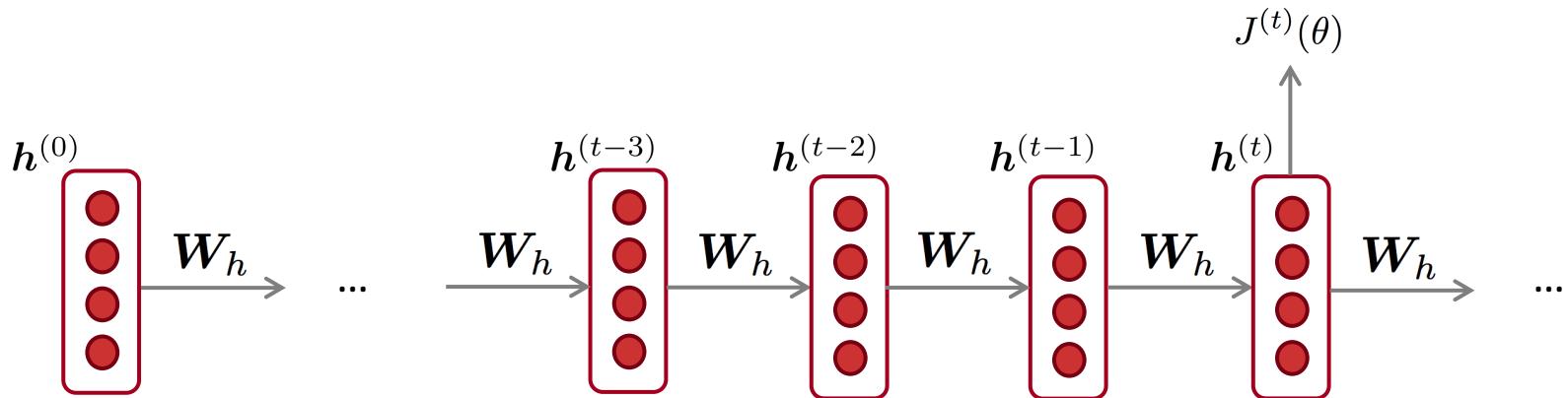
Training a RNN Language Model

- However: Computing loss and gradients across **entire corpus** is **too expensive**!
- Recall: **Stochastic Gradient Descent** allows us to compute loss and gradients for small chunk of data, and update.
- → In practice, consider $x^{(1)}, \dots, x^{(T)}$ as a **sentence**

$$J(\theta) = \frac{1}{T} \sum_{t=1}^T J^{(t)}(\theta)$$

- Compute loss $J(\theta)$ for a sentence (actually usually a batch of sentences), compute gradients and update weights. Repeat.

Backpropagation for RNNs



Question: What's the derivative of $J^{(t)}(\theta)$ w.r.t. the repeated weight matrix W_h ?

Answer:
$$\frac{\partial J^{(t)}}{\partial W_h} = \sum_{i=1}^t \frac{\partial J^{(t)}}{\partial W_h} \Big|_{(i)}$$

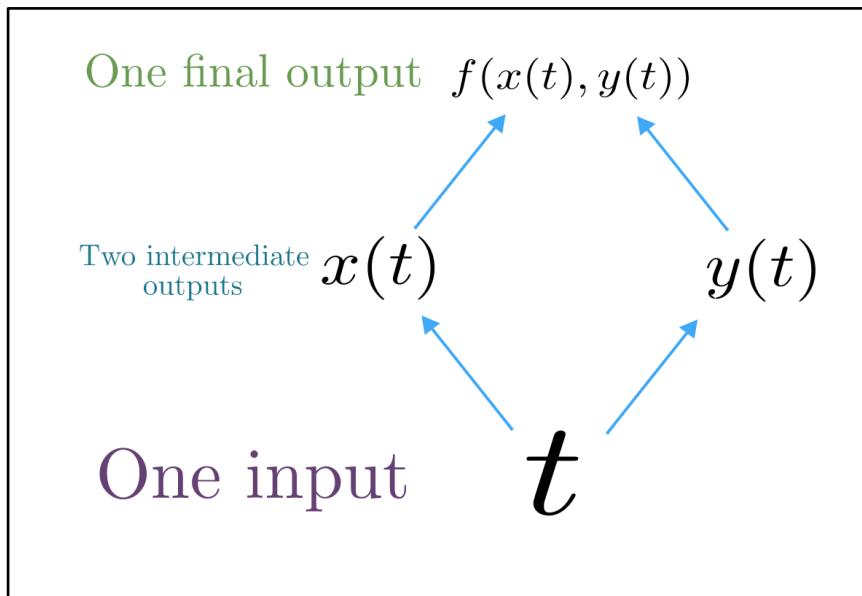
“The gradient w.r.t. a repeated weight is the sum of the gradient w.r.t. each time it appears”

Why?

Multivariable Chain Rule

- Given a multivariable function $f(x, y)$, and two single variable functions $x(t)$ and $y(t)$, here's what the multivariable chain rule says:

$$\underbrace{\frac{d}{dt} f(x(t), y(t))}_{\text{Derivative of composition function}} = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt}$$



Source:

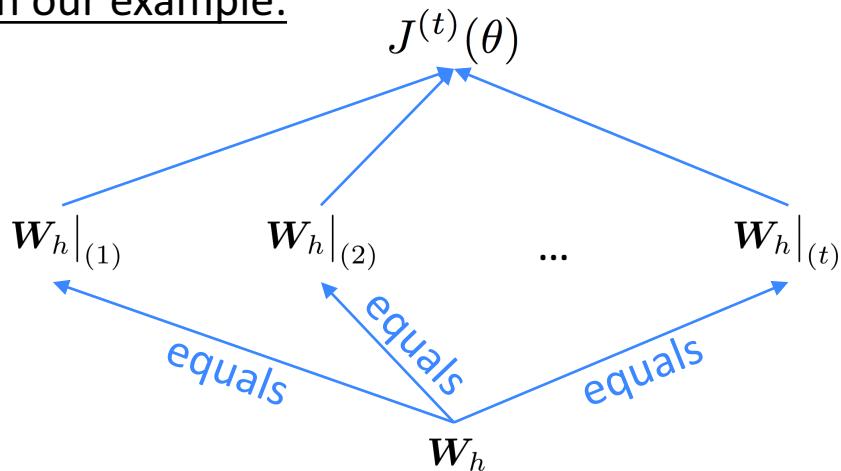
<https://www.khanacademy.org/math/multivariable-calculus/multivariable-derivatives/differentiating-vector-valued-functions/a/multivariable-chain-rule-simple-version>

Backpropagation for RNNs: Proof sketch

- Given a multivariable function $f(x, y)$, and two single variable functions $x(t)$ and $y(t)$, here's what the multivariable chain rule says:

$$\underbrace{\frac{d}{dt} f(\textcolor{teal}{x}(t), \textcolor{red}{y}(t))}_{\text{Derivative of composition function}} = \frac{\partial f}{\partial \textcolor{teal}{x}} \frac{d\textcolor{teal}{x}}{dt} + \frac{\partial f}{\partial \textcolor{red}{y}} \frac{d\textcolor{red}{y}}{dt}$$

In our example:



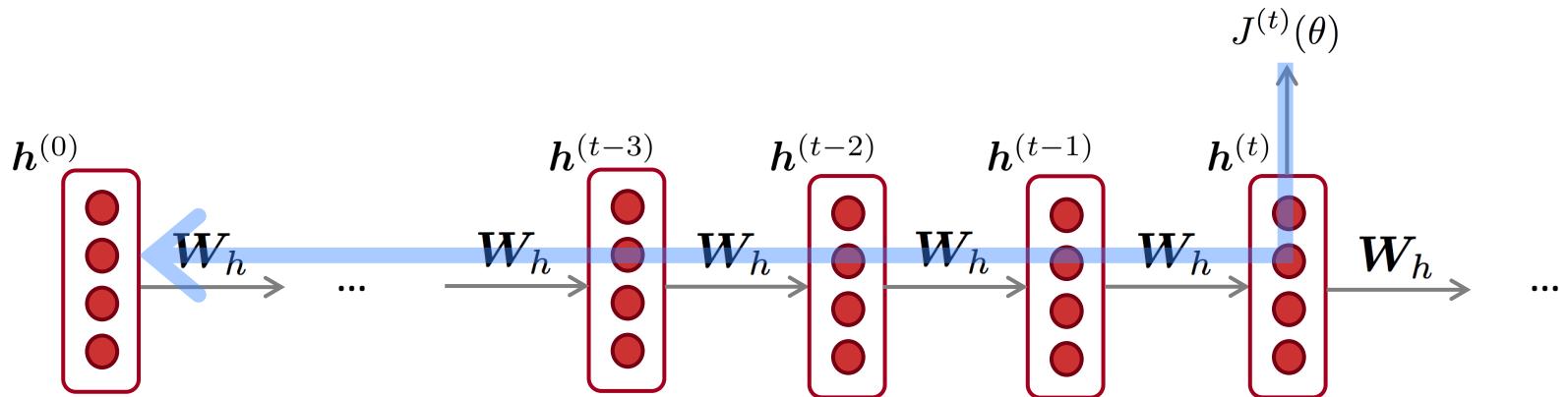
Apply the multivariable chain rule:

$$\begin{aligned}\frac{\partial J^{(t)}}{\partial \mathbf{W}_h} &= \sum_{i=1}^t \frac{\partial J^{(t)}}{\partial \mathbf{W}_h} \Big|_{(i)} \boxed{\frac{\partial \mathbf{W}_h|_{(i)}}{\partial \mathbf{W}_h}} \\ &= \sum_{i=1}^t \frac{\partial J^{(t)}}{\partial \mathbf{W}_h} \Big|_{(i)}\end{aligned}$$

Source:

<https://www.khanacademy.org/math/multivariable-calculus/multivariable-derivatives/differentiating-vector-valued-functions/a/multivariable-chain-rule-simple-version>

Backpropagation for RNNs



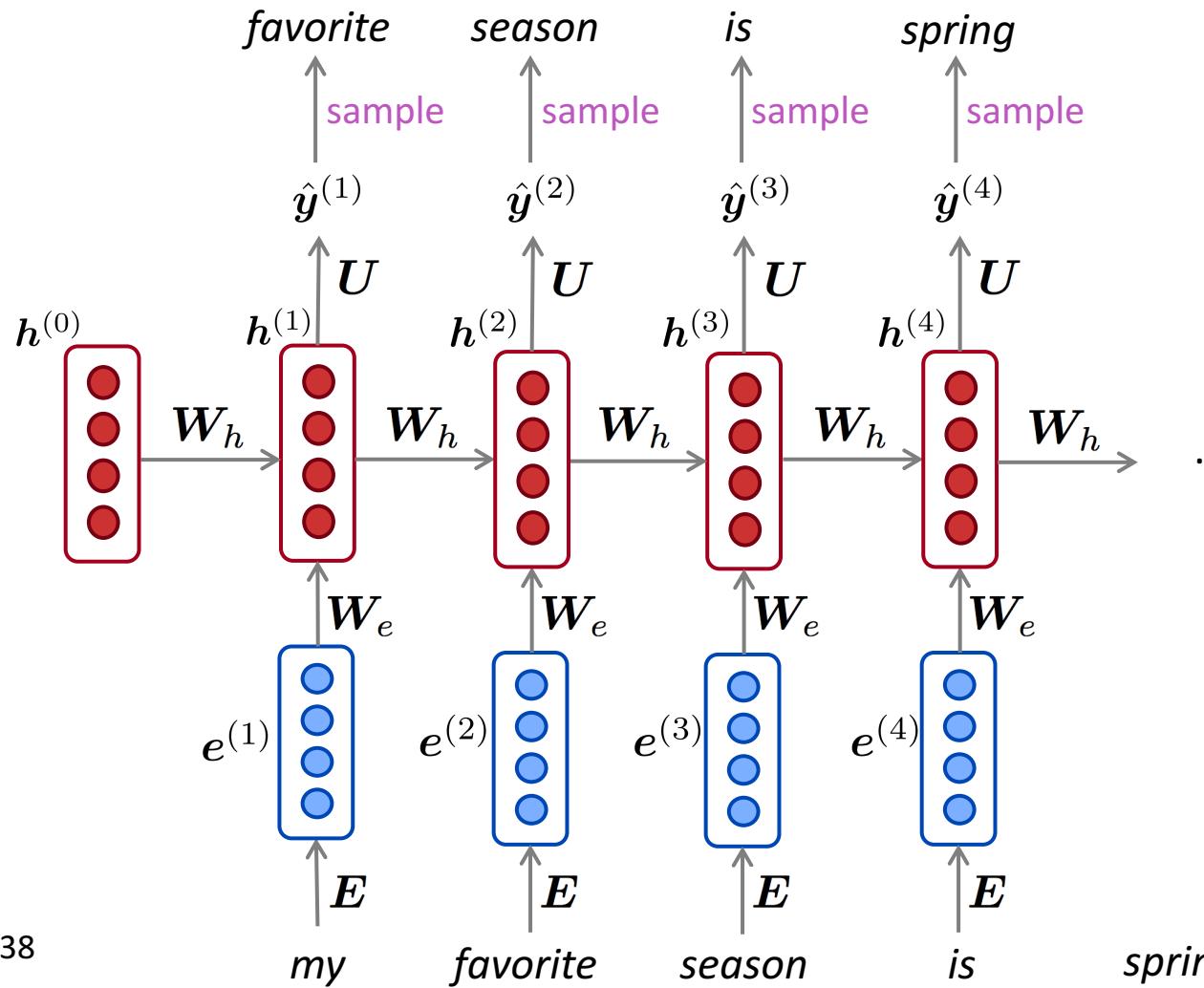
$$\frac{\partial J^{(t)}}{\partial \mathbf{W}_h} = \sum_{i=1}^t \left. \frac{\partial J^{(t)}}{\partial \mathbf{W}_h} \right|_{(i)}$$

Question: How do we calculate this?

Answer: Backpropagate over timesteps $i=t, \dots, 0$, summing gradients as you go.
This algorithm is called “backpropagation through time”

Generating text with a RNN Language Model

Just like a n-gram Language Model, you can use a RNN Language Model to generate text by repeated sampling. Sampled output is next step's input.



Generating text with a RNN Language Model

- Let's have some fun!
- You can train a RNN-LM on any kind of text, then generate text in that style.
- RNN-LM trained on Obama speeches:



The United States will step up to the cost of a new challenges of the American people that will share the fact that we created the problem. They were attacked and so that they have to say that all the task of the final days of war that I will not be able to get this done.

Source: <https://medium.com/@samim/obama-rnn-machine-generated-political-speeches-c8abd18a2ea0>

Generating text with a RNN Language Model

- Let's have some fun!
- You can train a RNN-LM on any kind of text, then generate text in that style.
- RNN-LM trained on *Harry Potter*:



“Sorry,” Harry shouted, panicking—“I’ll leave those brooms in London, are they?”

“No idea,” said Nearly Headless Nick, casting low close by Cedric, carrying the last bit of treacle Charms, from Harry’s shoulder, and to answer him the common room perched upon it, four arms held a shining knob from when the spider hadn’t felt it seemed. He reached the teams too.

Source: <https://medium.com/deep-writing/harry-potter-written-by-artificial-intelligence-8a9431803da6>

Generating text with a RNN Language Model

- Let's have some fun!
- You can train a RNN-LM on any kind of text, then generate text in that style.
- RNN-LM trained on *Seinfeld* scripts:



He slams his hand on the door. KRAMER enters dancing with garbage.

KRAMER

Hey hey hey, great idea for a big sponge: Make it so large you think it's got a fat clock in the middle.

JERRY

(takes off his bones)
Kramer, do you have a fun flashback to do?

Source: <https://www.avclub.com/a-bunch-of-comedy-writers-teamed-up-with-a-computer-to-1818633242>

Generating text with a RNN Language Model

- Let's have some fun!
- You can train a RNN-LM on any kind of text, then generate text in that style.
- (character-level) RNN-LM trained on paint colors:

Ghasty Pink	231	137	165	Sand Dan	201	172	143
Power Gray	151	124	112	Grade Bat	48	94	83
Navel Tan	199	173	140	Light Of Blast	175	150	147
Bock Coe White	221	215	236	Grass Bat	176	99	108
Horble Gray	178	181	196	Sindis Poop	204	205	194
Homestar Brown	133	104	85	Dope	219	209	179
Snader Brown	144	106	74	Testing	156	101	106
Golder Craam	237	217	177	Stoner Blue	152	165	159
Hurky White	232	223	215	Burble Simp	226	181	132
Burf Pink	223	173	179	Stanky Bean	197	162	171
Rose Hork	230	215	198	Turdly	190	164	116

Source: <http://aiweirdness.com/post/160776374467/new-paint-colors-invented-by-neural-network>

Evaluating Language Models

- The traditional **evaluation metric** for Language Models is **perplexity**.

$$PP = \prod_{t=1}^T \underbrace{\left(\frac{1}{\sum_{j=1}^{|V|} y_j^{(t)} \cdot \hat{y}_j^{(t)}} \right)}_{\text{Inverse probability of dataset}}^{1/T}$$

Normalized by
number of words

- Lower is better!**
- In Assignment 2 you will show that minimizing **perplexity** and minimizing the **loss function** are **equivalent**.

RNNs have greatly improved perplexity

n-gram model →

Increasingly complex RNNs ↓

Model	Perplexity
Interpolated Kneser-Ney 5-gram (Chelba et al., 2013)	67.6
RNN-1024 + MaxEnt 9-gram (Chelba et al., 2013)	51.3
RNN-2048 + BlackOut sampling (Ji et al., 2015)	68.3
Sparse Non-negative Matrix factorization (Shazeer et al., 2015)	52.9
LSTM-2048 (Jozefowicz et al., 2016)	43.7
2-layer LSTM-8192 (Jozefowicz et al., 2016)	30
Ours small (LSTM-2048)	43.9
Ours large (2-layer LSTM-2048)	39.8

Perplexity improves
(lower is better)

Source: <https://research.fb.com/building-an-efficient-neural-language-model-over-a-billion-words/>

Why should we care about Language Modeling?

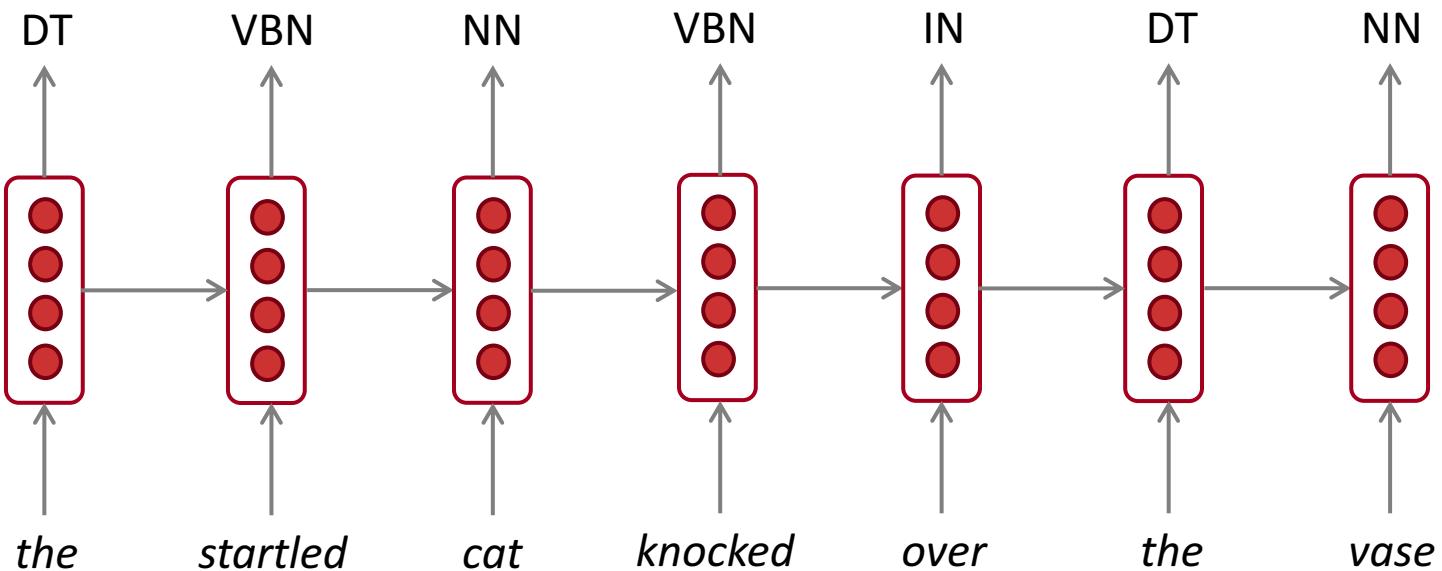
- Language Modeling is a **subcomponent** of other NLP systems:
 - Speech recognition
 - Use a LM to generate transcription, **conditioned** on audio
 - Machine Translation
 - Use a LM to generate translation, **conditioned** on original text
 - Summarization
 - Use a LM to generate summary, **conditioned** on original text
 - Language Modeling is a **benchmark task** that helps us **measure our progress** on understanding language
- 
- These systems are called *conditional Language Models*

Recap

- Language Model: A system that predicts the next word
- Recurrent Neural Network: A family of neural networks that:
 - Take sequential input of any length
 - Apply the same weights on each step
 - Can optionally produce output on each step
- Recurrent Neural Network \neq Language Model
- We've shown that RNNs are a great way to build a LM.
- But RNNs are useful for much more!

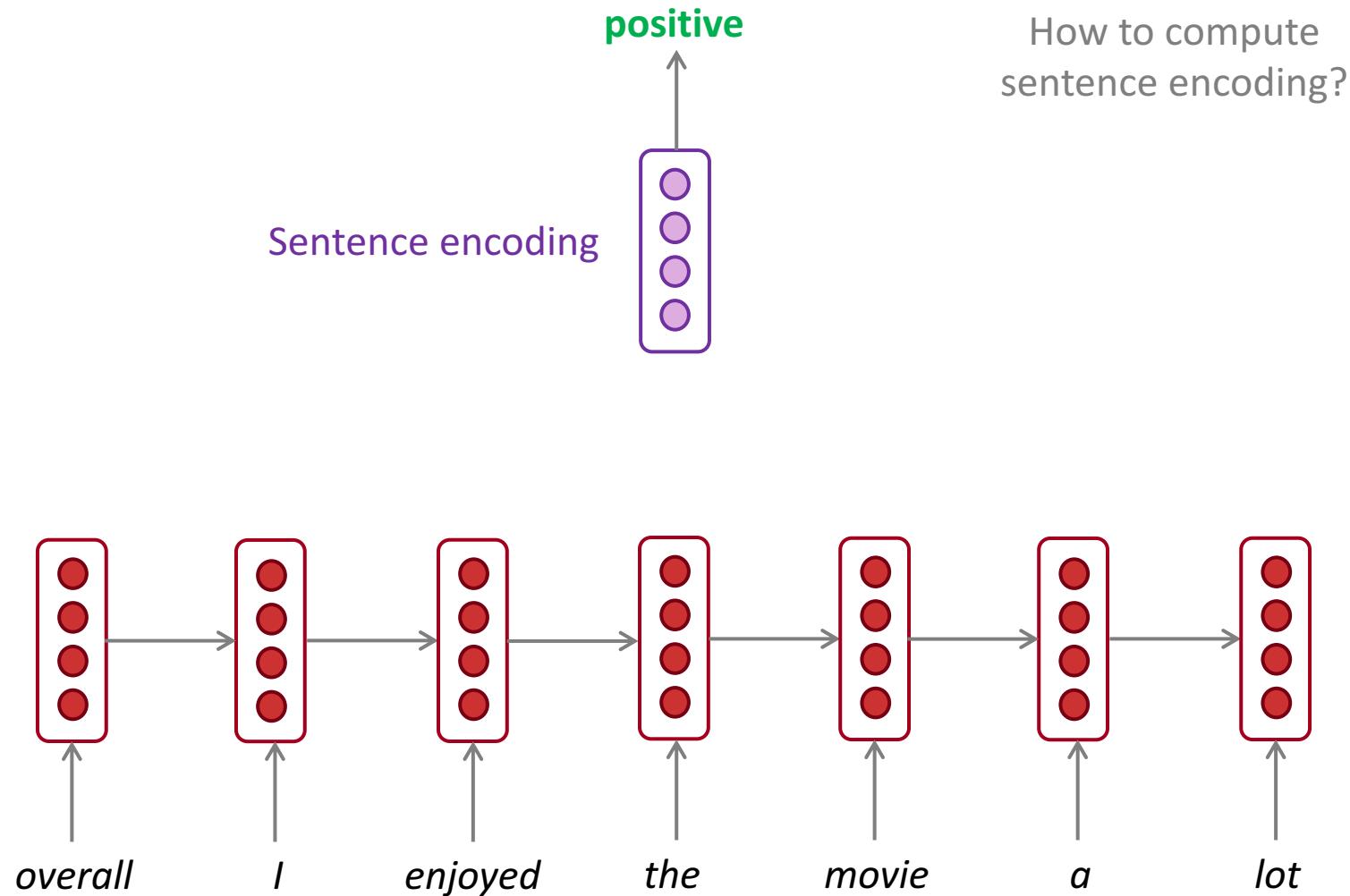
RNNs can be used for tagging

e.g. part-of-speech tagging, named entity recognition



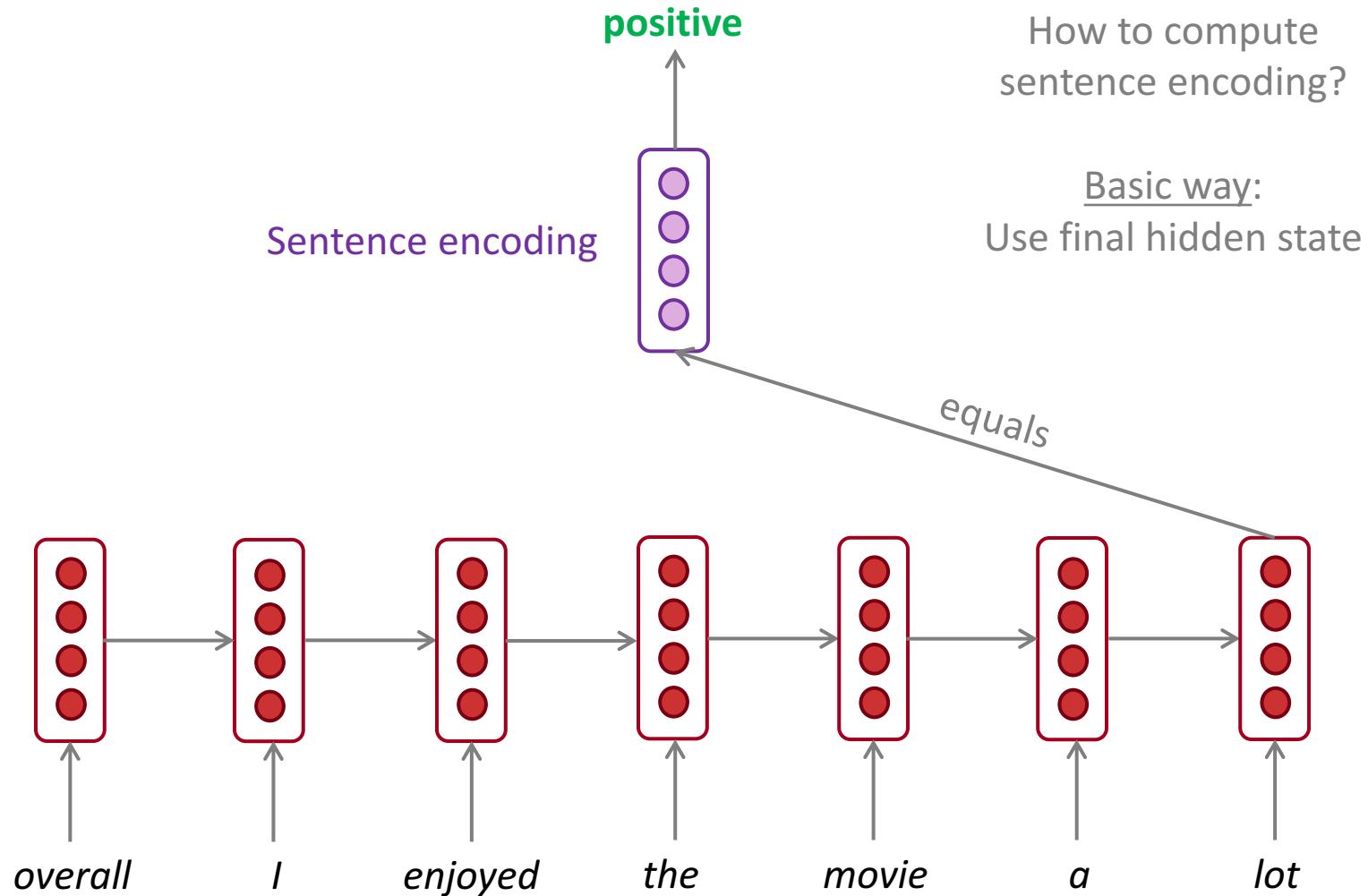
RNNs can be used for sentence classification

e.g. sentiment classification



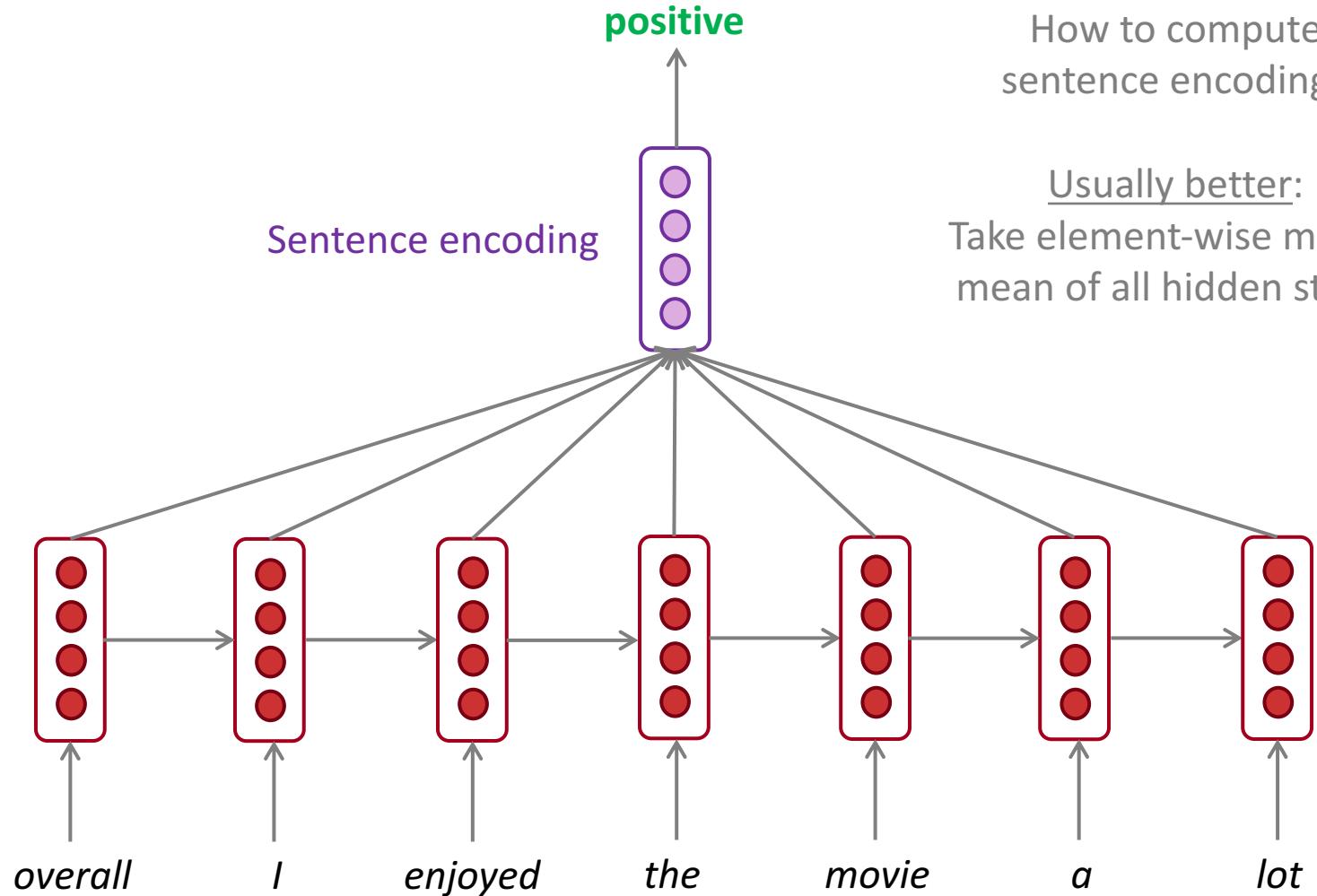
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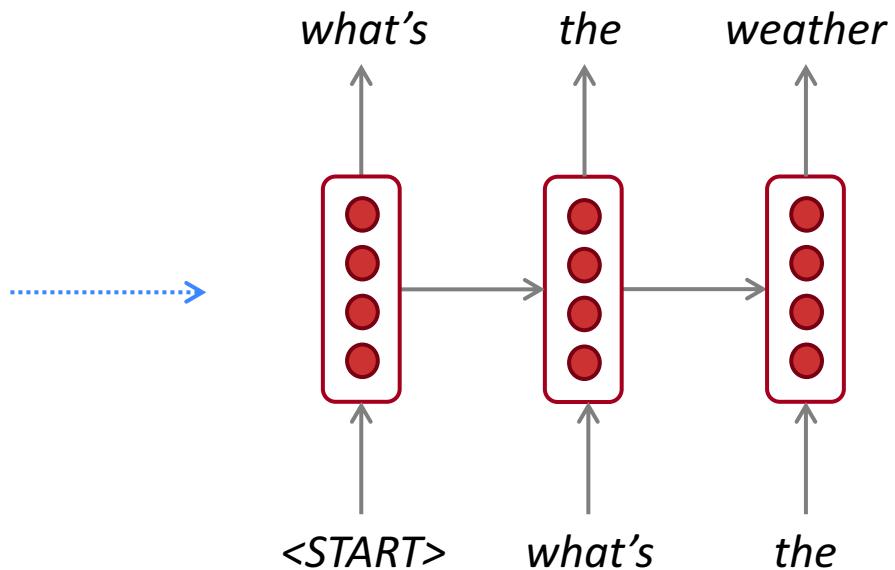
RNNs can be used for sentence classification

e.g. sentiment classification



RNNs can be used to generate text

e.g. speech recognition, machine translation, summarization

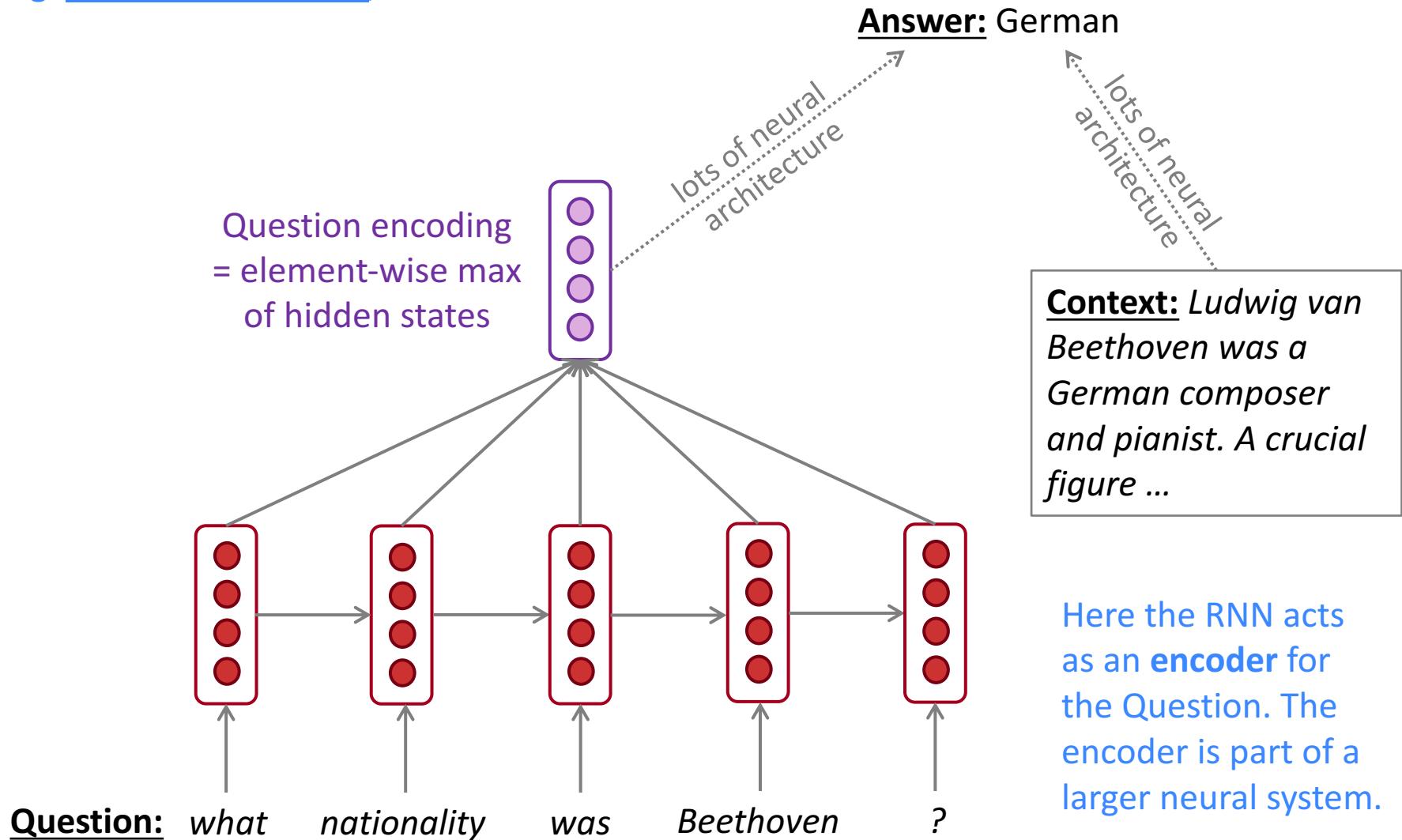


Remember: these are called “conditional language models”.

We’ll see Machine Translation in much more detail later.

RNNs can be used as an encoder module

e.g. question answering, machine translation



A note on terminology

RNN described in this lecture = “vanilla RNN”



Next lecture: You will learn about other RNN flavors

like **GRU**



and **LSTM**



and multi-layer RNNs



By the end of the course: You will understand phrases like

“stacked bidirectional LSTM with residual connections and self-attention”



Next time

- Problems with RNNs!
 - Vanishing gradients

motivates

- 
- 1. Only one way (left=>right)
 - 2. Vanishing gradients while collecting deltas from previous gradient in only one back-prop

- Fancy RNN variants!
 - LSTM
 - GRU
 - multi-layer
 - bidirectional