Lecture 6:
Language Models and
Recurrent Neural Networks

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Overview

Today we will:

• Introduce a new NLP task
  • Language Modeling

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

These are two of the most important ideas for the rest of the class!
Language Modeling

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

  \[ \text{the students opened their } \_\_\_\_\_ \]

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

  \[
P(x^{(t+1)} \mid x^{(t)}, \ldots, x^{(1)})
  \]

  where \( x^{(t+1)} \) can be any word in the vocabulary \( V = \{w_1, \ldots, w_{|V|}\} \)

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

- You can also think of a Language Model as a system that assigns probability to a piece of text.

- For example, if we have some text $x^{(1)}, \ldots, x^{(T)}$, then the probability of this text (according to the Language Model) is:

$$P(x^{(1)}, \ldots, x^{(T)}) = P(x^{(1)}) \times P(x^{(2)}| x^{(1)}) \times \cdots \times P(x^{(T)}| x^{(T-1)}, \ldots, x^{(1)})$$

$$= \prod_{t=1}^{T} P(x^{(t)}| x^{(t-1)}, \ldots, x^{(1)})$$

This is what our LM provides
You use Language Models every day!
You use Language Models every day!

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
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.
  - unigrams: “the”, “students”, “opened”, “their”
  - bigrams: “the students”, “students opened”, “opened their”
  - trigrams: “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: $x^{(t+1)}$ depends only on the preceding $n-1$ words.

$$P(x^{(t+1)}|x^{(t)}, \ldots, x^{(1)}) = P(x^{(t+1)}|x^{(t)}, \ldots, x^{(t-n+2)})$$

**Assumption**

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

$$\approx \frac{\text{count}(x^{(t+1)}, x^{(t)}, \ldots, x^{(t-n+2)})}{\text{count}(x^{(t)}, \ldots, x^{(t-n+2)})}$$

**(statistical approximation)**
n-gram Language Models: Example

Suppose we are learning a 4-gram Language Model.

\[
P(w | \text{students opened their}) = \frac{\text{count}(\text{students opened their } w)}{\text{count}(\text{students opened their})}
\]

For example, suppose that in the corpus:

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

Should we have discarded the “proctor” context?
**Sparsity Problems with n-gram Language Models**

**Sparsity Problem 1**

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

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

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

**Sparsity Problem 2**

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

**(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.
Storage Problems with n-gram Language Models

**Storage:** Need to store count for all \( n \)-grams you saw in the corpus.

\[
P(w | \text{students opened their}) = \frac{\text{count(students opened their } w)}{\text{count(students opened their)}}
\]

Increasing \( n \) or increasing corpus increases model size!
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*

* Try for yourself: https://nlpforhackers.io/languagemodels/

Otherwise, seems reasonable!

Sparsity problem: not much granularity in the probability distribution

Business and financial news

today the ________

generate probability distribution

<table>
<thead>
<tr>
<th>Word</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>company</td>
<td>0.153</td>
</tr>
<tr>
<td>bank</td>
<td>0.153</td>
</tr>
<tr>
<td>price</td>
<td>0.077</td>
</tr>
<tr>
<td>italian</td>
<td>0.039</td>
</tr>
<tr>
<td>emirate</td>
<td>0.039</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>
Generating text with a n-gram Language Model

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

today the _______

condition on this
get probability distribution

<table>
<thead>
<tr>
<th></th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>company</td>
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</tr>
<tr>
<td>emirate</td>
<td>0.039</td>
</tr>
<tr>
<td>...</td>
<td></td>
</tr>
</tbody>
</table>
Generating text with a n-gram Language Model

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

```plaintext
today the price _______
```

Condition on this

Get probability distribution

<table>
<thead>
<tr>
<th>sample</th>
<th>of</th>
<th>for</th>
<th>it</th>
<th>to</th>
<th>is</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.308</td>
<td>0.050</td>
<td>0.046</td>
<td>0.046</td>
<td>0.031</td>
</tr>
</tbody>
</table>
```

Generating text with a n-gram Language Model

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

*today the price of*****

c-condition on this

get probability distribution

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>the</td>
<td>0.072</td>
</tr>
<tr>
<td>18</td>
<td>0.043</td>
</tr>
<tr>
<td>oil</td>
<td>0.043</td>
</tr>
<tr>
<td>its</td>
<td>0.036</td>
</tr>
<tr>
<td>gold</td>
<td>0.018</td>
</tr>
</tbody>
</table>

sample
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.

Surprisingly grammatical!

...but incoherent. We need to consider more than three words at a time if we want to model language well.

But increasing n worsens sparsity problem, and increases model size...
How to build a *neural* Language Model?

- Recall the Language Modeling task:
  - Input: sequence of words $x^{(1)}, x^{(2)}, \ldots, x^{(t)}$
  - Output: prob dist of the next word $P(x^{(t+1)} | x^{(t)}, \ldots, x^{(1)})$

- How about a `window-based neural model`?
  - We saw this applied to Named Entity Recognition in Lecture 3:

```
museums in Paris are amazing
```
A fixed-window neural Language Model

as the proctor started the clock
discard

the students opened their _____ fixed window
A fixed-window neural Language Model

output distribution
\[ \hat{y} = \text{softmax}(Uh + b_2) \in \mathbb{R}^{|V|} \]

hidden layer
\[ h = f(We + b_1) \]

concatenated word embeddings
\[ e = [e^{(1)}; e^{(2)}; e^{(3)}; e^{(4)}] \]

words / one-hot vectors
\[ x^{(1)}, x^{(2)}, x^{(3)}, x^{(4)} \]
A fixed-window neural Language Model

**Improvements** over *n*-gram LM:
- No sparsity problem
- Don’t need to store all observed *n*-grams

Remaining **problems:**
- Fixed window is too small
- Enlarging window enlarges \( W \)
- Window can never be large enough!
- \( x^{(1)} \) and \( x^{(2)} \) are multiplied by completely different weights in \( W \).
  No symmetry in how the inputs are processed.

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
A RNN Language Model

Output distribution
\[ \hat{y}^{(t)} = \text{softmax} \left( U h^{(t)} + b_2 \right) \in \mathbb{R}^{V} \]

Hidden states
\[ h^{(t)} = \sigma \left( W_h h^{(t-1)} + W_e e^{(t)} + b_1 \right) \]

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

Word embeddings
\[ e^{(t)} = E x^{(t)} \]

Words / One-hot vectors
\[ x^{(t)} \in \mathbb{R}^{V} \]

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
- Computation for step $t$ can (in theory) use information from many steps back
- Model size doesn’t increase for longer input
- Same weights applied on every timestep, so there is symmetry in how inputs are processed.

RNN Disadvantages:

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

More on these later in the course
Training a RNN Language Model

- Get a big corpus of text which is a sequence of words \( x^{(1)}, \ldots, x^{(T)} \)
- Feed into RNN-LM; compute output distribution \( \hat{y}^{(t)} \) for every step \( t \).
  - i.e. predict probability dist of every word, given words so far

- Loss function on step \( t \) is cross-entropy between predicted probability distribution \( \hat{y}^{(t)} \), and the true next word \( y^{(t)} \) (one-hot for \( x^{(t+1)} \)):

\[
J^{(t)}(\theta) = CE(y^{(t)}, \hat{y}^{(t)}) = - \sum_{w \in V} y_w^{(t)} \log \hat{y}_w^{(t)} = - \log \hat{y}_{x_{t+1}}^{(t)}
\]

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

\[
J(\theta) = \frac{1}{T} \sum_{t=1}^{T} J^{(t)}(\theta) = \frac{1}{T} \sum_{t=1}^{T} - \log \hat{y}_{x_{t+1}}^{(t)}
\]
Training a RNN Language Model

\[ J^{(1)}(\theta) = \text{negative log prob of "students" } \]

**Loss** → \[ h^{(0)} \rightarrow W_h \rightarrow h^{(1)} \rightarrow U \rightarrow \hat{y}^{(1)} \]

**Predicted prob dists** → \[ \hat{y}^{(2)} \rightarrow U \rightarrow \hat{y}^{(2)} \]

**Corpus** → \[ x^{(1)} \rightarrow E \rightarrow e^{(1)} \rightarrow W_e \rightarrow \hat{y}^{(1)} \]

\[ x^{(2)} \rightarrow E \rightarrow e^{(2)} \rightarrow W_e \rightarrow \hat{y}^{(2)} \]

\[ x^{(3)} \rightarrow E \rightarrow e^{(3)} \rightarrow W_e \rightarrow \hat{y}^{(3)} \]

\[ x^{(4)} \rightarrow E \rightarrow e^{(4)} \rightarrow W_e \rightarrow \hat{y}^{(4)} \]

...
Training a RNN Language Model

Loss $\rightarrow J^{(1)}(\theta)$

Predicted prob dists $\rightarrow \hat{y}^{(1)}$

$h^{(0)} \rightarrow W_h h^{(1)}$

$\hat{y}^{(1)} \rightarrow U$

$J^{(2)}(\theta) = \text{negative log prob of “opened”}$

$h^{(1)} \rightarrow W_h h^{(2)}$

$\hat{y}^{(2)} \rightarrow U$

$J^{(3)}(\theta)$

$h^{(2)} \rightarrow W_h h^{(3)}$

$\hat{y}^{(3)} \rightarrow U$

$J^{(4)}(\theta)$

$h^{(3)} \rightarrow W_h h^{(4)}$

$\hat{y}^{(4)} \rightarrow U$

$h^{(4)} \rightarrow W_h \rightarrow \ldots$

$W_e \rightarrow e^{(1)}$

$W_e \rightarrow e^{(2)}$

$W_e \rightarrow e^{(3)}$

$W_e \rightarrow e^{(4)}$

$E \rightarrow \hat{y}^{(1)}$

$E \rightarrow \hat{y}^{(2)}$

$E \rightarrow \hat{y}^{(3)}$

$E \rightarrow \hat{y}^{(4)}$

$E \rightarrow \ldots$

Corpus $\rightarrow x^{(1)}$

Corpus $\rightarrow x^{(2)}$

Corpus $\rightarrow x^{(3)}$

Corpus $\rightarrow x^{(4)}$

Corpus $\rightarrow \ldots$

$x^{(1)}$ the

$x^{(2)}$ students

$x^{(3)}$ opened

$x^{(4)}$ their

exams
Training a RNN Language Model

\[ J^{(1)}(\theta) \xrightarrow{\text{Loss}} J^{(2)}(\theta) \]

\[ = \text{negative log prob of “their”} \]

\[ \mathbf{h}^{(0)} \xrightarrow{W_h} \mathbf{h}^{(1)} \]

\[ \mathbf{e}^{(1)} \xrightarrow{E} \text{the} \]

\[ \mathbf{x}^{(1)} \]

\[ \mathbf{h}^{(2)} \xrightarrow{W_h} \mathbf{h}^{(3)} \]

\[ \mathbf{e}^{(2)} \xrightarrow{E} \text{students} \]

\[ \mathbf{x}^{(2)} \]

\[ \mathbf{h}^{(3)} \xrightarrow{W_h} \mathbf{h}^{(4)} \]

\[ \mathbf{e}^{(3)} \xrightarrow{E} \text{opened} \]

\[ \mathbf{x}^{(3)} \]

\[ \mathbf{h}^{(4)} \xrightarrow{W_h} \]

\[ \mathbf{e}^{(4)} \xrightarrow{E} \text{their} \]

\[ \mathbf{x}^{(4)} \]

\[ \cdots \]

\[ \text{exams} \]

\[ ... \]
Training a RNN Language Model

Loss \rightarrow J^{(1)}(\theta) \rightarrow \hat{y}^{(1)} \rightarrow u \rightarrow h^{(1)} \rightarrow \cdots \rightarrow \hat{y}^{(4)} = \text{negative log prob of “exams”}

Predicted prob dists

Corpus \rightarrow \text{the} \rightarrow \text{students} \rightarrow \text{opened} \rightarrow \text{their} \rightarrow \text{exams} \rightarrow \cdots
Training a RNN Language Model

\[
J(1)(\theta) + J(2)(\theta) + J(3)(\theta) + J(4)(\theta) + \ldots = J(\theta) = \frac{1}{T} \sum_{t=1}^{T} J^{(t)}(\theta)
\]

\[
\begin{align*}
&h(0) \rightarrow W_h \rightarrow W_e \rightarrow E \\
&h(1) \rightarrow W_h \rightarrow W_e \rightarrow E \\
&h(2) \rightarrow W_h \rightarrow W_e \rightarrow E \\
&h(3) \rightarrow W_h \rightarrow W_e \rightarrow E \\
&h(4) \rightarrow W_h \rightarrow W_e \rightarrow E \\
\end{align*}
\]

Corpus: the students opened their exams ...

Predicted prob dists: \(\hat{y}(1), \hat{y}(2), \hat{y}(3), \hat{y}(4)\)

Loss: \(J(1)(\theta), J(2)(\theta), J(3)(\theta), J(4)(\theta), \ldots\)
Training a RNN Language Model

• However: Computing loss and gradients across entire corpus \( x^{(1)}, \ldots, x^{(T)} \) is too expensive!

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

• In practice, consider \( x^{(1)}, \ldots, x^{(T)} \) as a sentence (or a document)

• Recall: Stochastic Gradient Descent allows us to compute loss and gradients for small chunk of data, and update.

• Compute loss \( J(\theta) \) for a sentence (actually a batch of sentences), compute gradients and update weights. Repeat.
Question: What’s the derivative of $J^{(t)}(\theta)$ w.r.t. the repeated weight matrix $W_h$?

Answer: \[
\frac{\partial J^{(t)}}{\partial W_h} = \sum_{i=1}^{t} \left[ \frac{\partial J^{(t)}}{\partial W_h} \right]_{(i)}
\]

“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:

\[
\frac{d}{dt} f(x(t), y(t)) = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt}
\]

Derivative of composition function

Source:
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:

$$\frac{d}{dt} f(x(t), y(t)) = \frac{\partial f}{\partial x} \frac{dx}{dt} + \frac{\partial f}{\partial y} \frac{dy}{dt}$$

Derivative of composition function

---

In our example:

$J^{(t)}(\theta)$

$W_h(1)$ $W_h(2)$ $...$ $W_h(t)$

Apply the multivariable chain rule:

$$\frac{\partial J^{(t)}}{\partial W_h} = \sum_{i=1}^{t} \frac{\partial J^{(t)}}{\partial W_h} \frac{\partial W_h}{\partial W_h} = 1$$

Source:
Backpropagation for RNNs

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

Question: How do we calculate this?
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.

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 recipes:

  Title: CHOCOLATE RANCH BARBECUE
  Categories: Game, Casseroles, Cookies, Cookies
  Yield: 6 Servings

  2 tb Parmesan cheese -- chopped
  1 c Coconut milk
  3 Eggs, beaten

  Place each pasta over layers of lumps. Shape mixture into the moderate oven and simmer until firm. Serve hot in bodied fresh, mustard, orange and cheese.

  Combine the cheese and salt together the dough in a large skillet; add the ingredients and stir in the chocolate and pepper.

  Source: https://gist.github.com/nylki/1efbaa36635956d35bcc
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 paint color names:

  This is an example of a **character-level RNN-LM** (predicts what character comes next)

Evaluating Language Models

• The standard evaluation metric for Language Models is perplexity.

\[
\text{perplexity} = \prod_{t=1}^{T} \left( \frac{1}{P_{LM}(x^{(t+1)} | x^{(t)}, \ldots, x^{(1)})} \right)^{1/T}
\]

Inverse probability of corpus, according to Language Model

• This is equal to the exponential of the cross-entropy loss \( J(\theta) \):

\[
= \prod_{t=1}^{T} \left( \frac{1}{\hat{y}^{(t)}_{x_{t+1}}} \right)^{1/T} = \exp \left( \frac{1}{T} \sum_{t=1}^{T} - \log \hat{y}^{(t)}_{x_{t+1}} \right) = \exp(J(\theta))
\]

Lower perplexity is better!
RNNs have greatly improved perplexity

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

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 **benchmark task** that helps us **measure our progress** on understanding language.

• Language Modeling is a **subcomponent** of many NLP tasks, especially those involving **generating text** or estimating the probability of text:
  
  • Predictive typing
  • Speech recognition
  • Handwriting recognition
  • Spelling/grammar correction
  • Authorship identification
  • Machine translation
  • Summarization
  • Dialogue
  • etc.
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 ≠ 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

How to compute sentence encoding?

Sentence encoding

overall  I  enjoyed  the  movie  a  lot
RNNs can be used for sentence classification
e.g. sentiment classification

How to compute sentence encoding?

Basic way: Use final hidden state

Sentence encoding

positive

Overall I enjoyed the movie a lot
RNNs can be used for sentence classification
e.g. sentiment classification

Sentence encoding

positive

How to compute sentence encoding?

Usually better: Take element-wise max or mean of all hidden states

overall  I  enjoyed  the  movie  a  lot
RNNs can be used as an encoder module
e.g. question answering, machine translation, many other tasks!

Here the RNN acts as an encoder for the Question (the hidden states represent the Question). The encoder is part of a larger neural system.

Answer: German

Context: Ludwig van Beethoven was a German composer and pianist. A crucial figure ...

Question: what nationality was Beethoven?
RNN-LMs can be used to generate text

e.g. speech recognition, machine translation, summarization

This is an example of a conditional language model. We’ll see Machine Translation in much more detail later.
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

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