Language modeling

CS 685, Fall 2021
Advanced Natural Language Processing
http://people.cs.umass.edu/~miyyer/cs685/

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Do class projects ever get turned into research papers after the course?
On a few occasions! We have had some papers in NLP conferences as well as workshops that were final projects in 585/685.

Can I choose a “simple” paper for the HW0 paper review?
Sure, as long as your response fulfills all of the stated criteria

HW0 deadline is very soon and we haven’t learned anything to help us do it!
After this lecture, you should have everything you need (resources are provided in the HW to learn how PyTorch works)

Let’s say I want to train a model for *sentiment analysis*

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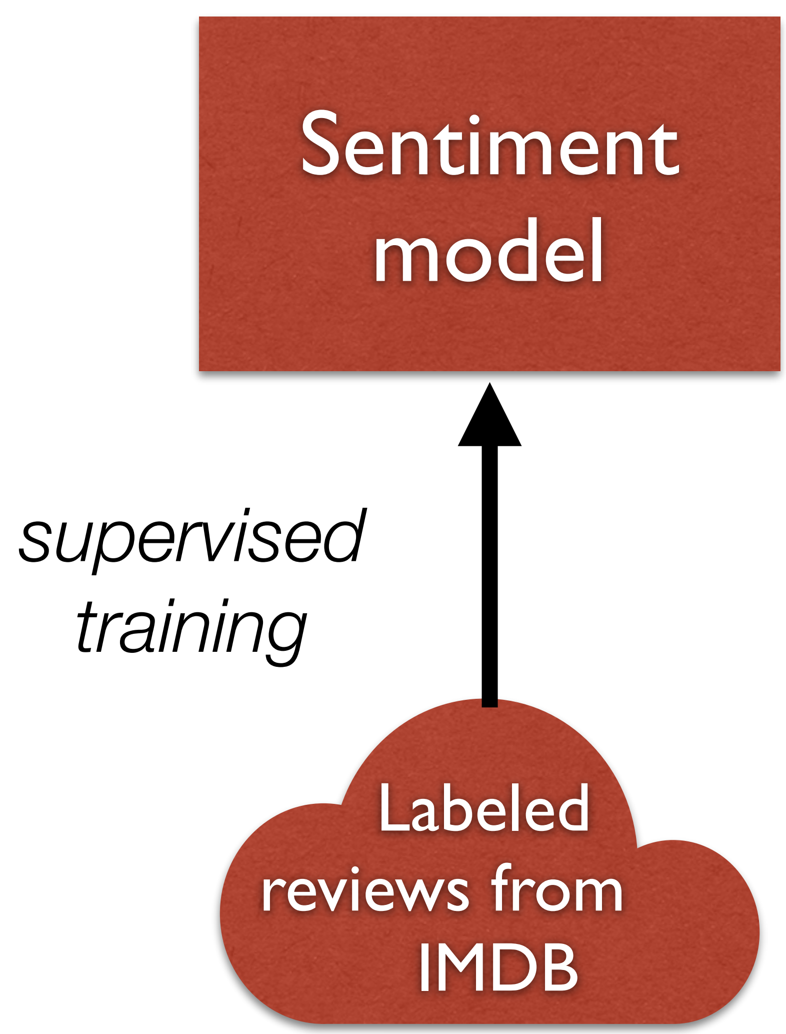
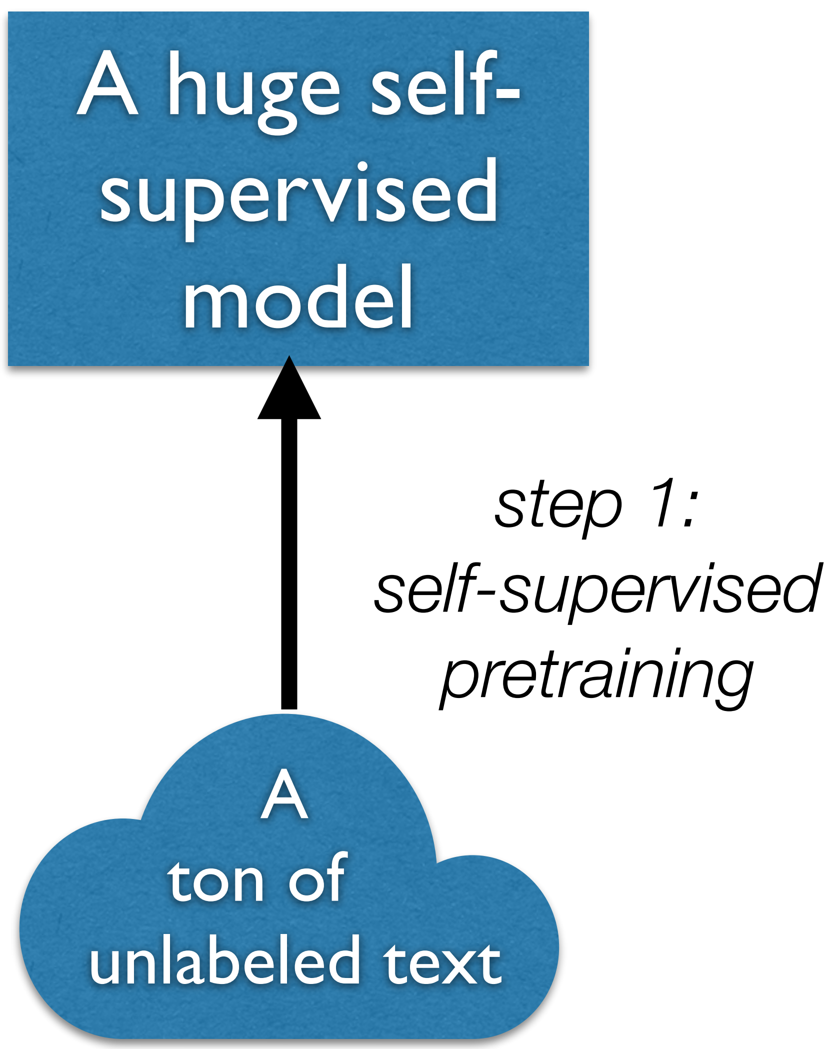
In the past, I would simply train a *supervised* model on labeled sentiment examples (i.e., review text / score pairs from IMDB)



Let's say I want to train a model for *sentiment analysis*

Nowadays, however, we use *transfer learning*:



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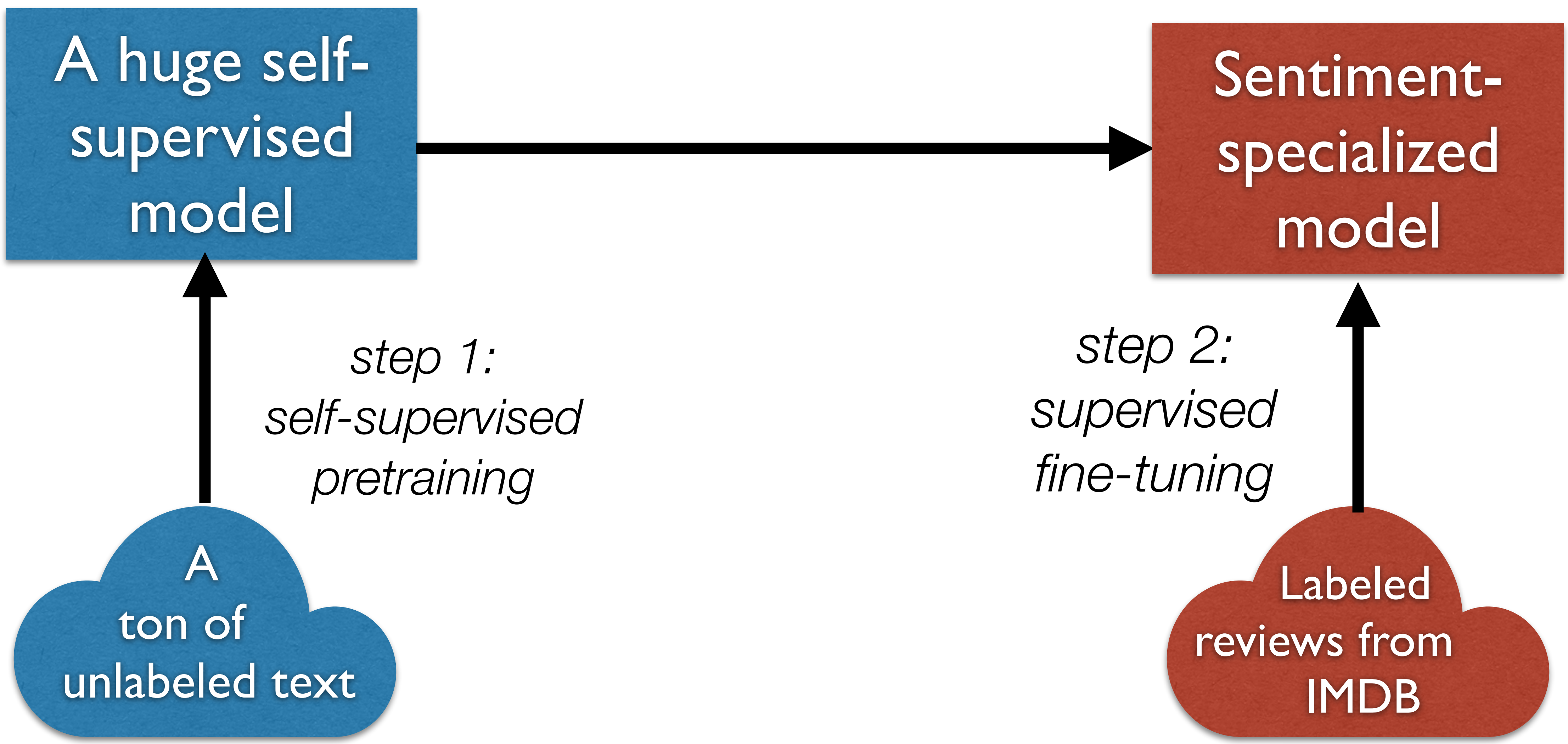
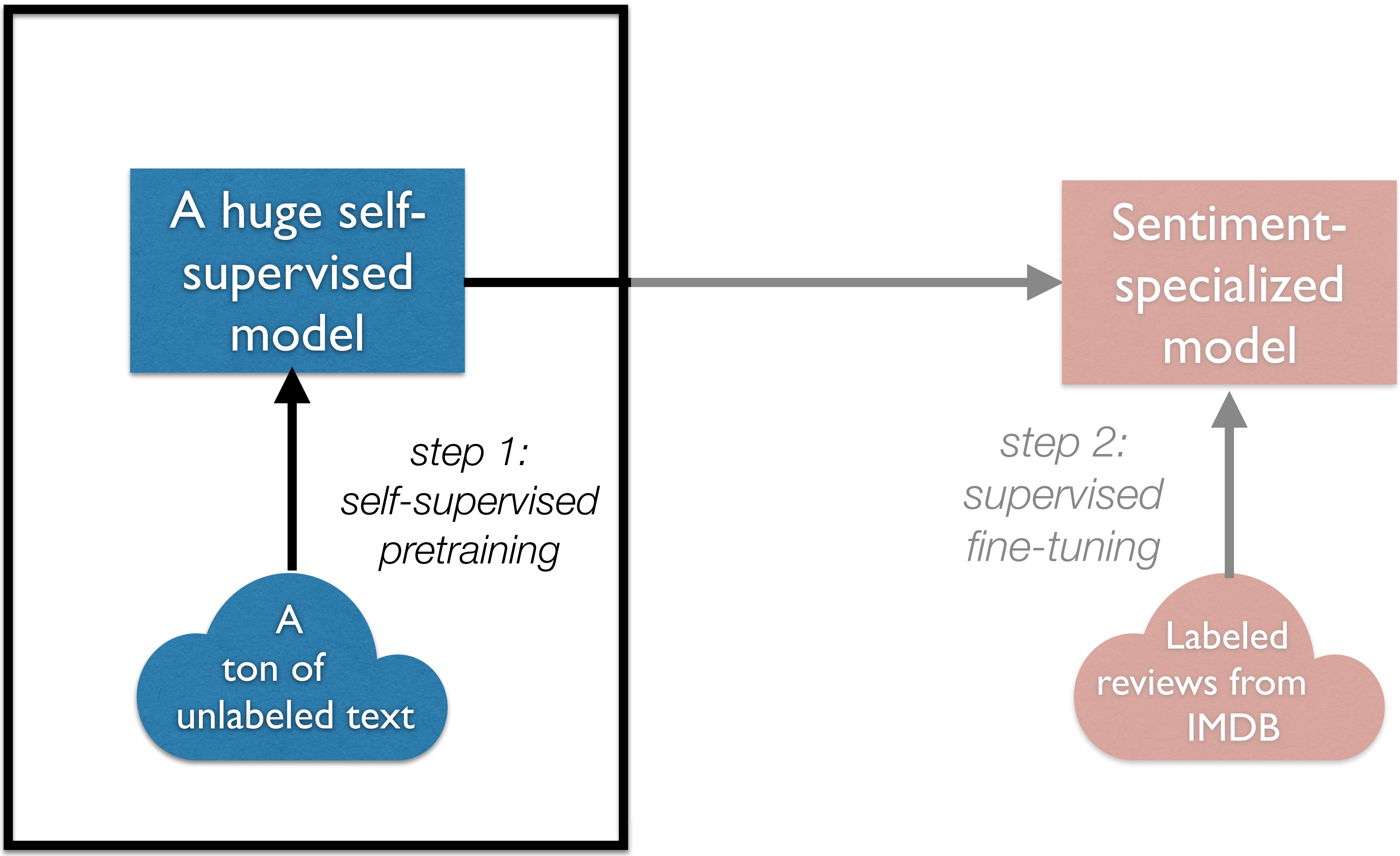


This lecture: **language modeling**, which forms the core of most self-supervised NLP approaches



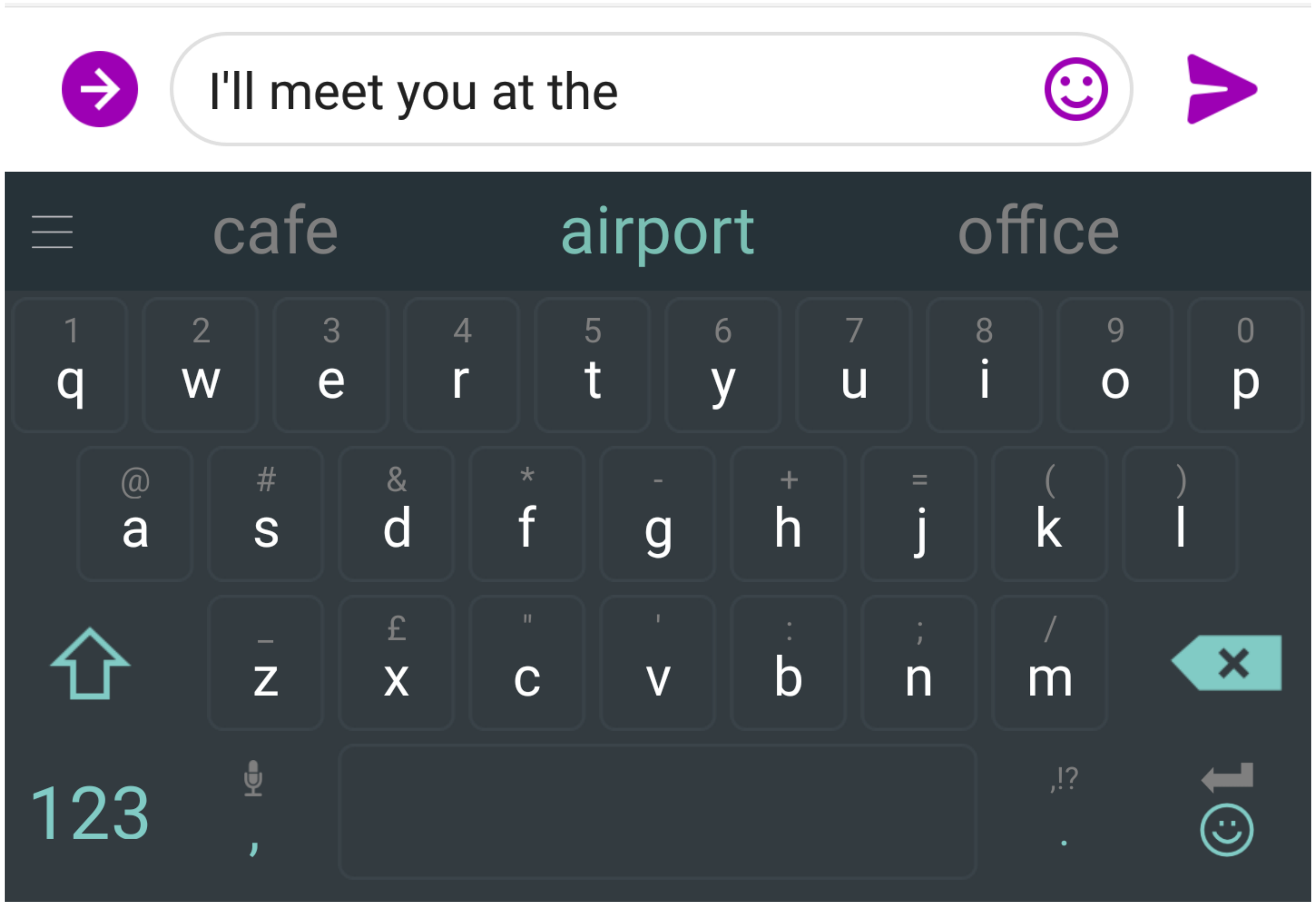
Language models assign a probability to a piece of text

- why would we ever want to do this?

- translation:
  - P(i flew to the movies) **<<<<<** P(i went to the movies)

- speech recognition:
  - P(i saw a van) **>>>>>** P(eyes awe of an)

You use Language Models every day!



You use Language Models every day!

Probabilistic Language Modeling

- Goal: compute the probability of a sentence or sequence of words:

$$P(W) = P(w_1,w_2,w_3,w_4,w_5 \ldots w_n)$$

- Related task: probability of an upcoming word:

$$P(w_5|w_1,w_2,w_3,w_4)$$

- A model that computes either of these:

$P(W)$ or $P(w_n|w_1,w_2 \ldots w_{n-1})$ is called a **language model** or **LM**

How to compute P(W)

- How to compute this joint probability:
  - P(its, water, is, so, transparent, that)
- Intuition: let’s rely on the Chain Rule of Probability

Reminder: The Chain Rule

- Recall the definition of conditional probabilities

  $\mathbf{P(B|A) = P(A,B)/P(A)}$ Rewriting: $\mathbf{P(A,B) = P(A)P(B|A)}$

- More variables:

  $P(A,B,C,D) = P(A)P(B|A)P(C|A,B)P(D|A,B,C)$

- The Chain Rule in General

  $P(x_1,x_2,x_3,\ldots,x_n) = P(x_1)P(x_2|x_1)P(x_3|x_1,x_2)\ldots P(x_n|x_1,\ldots,x_{n-1})$

The Chain Rule applied to compute joint probability of words in sentence

$$P(w_1 w_2 \ldots w_n) = \prod_i P(w_i \mid w_1 w_2 \ldots w_{i-1})$$

P("its water is so transparent") =
P(its) × P(water|its) × P(is|its water)
× P(so|its water is) × P(transparent|its water is so)

The Chain Rule applied to compute joint probability of words in sent

$$P(w_1 w_2 \ldots w_n) = \prod_i P(w_i \mid \overbrace{w_1 w_2 \ldots w_{i-1}}^{\text{In HW0, we refer to this as a “prefix”}})$$

P(“its water is so transparent”) =

P(its) × P(water|its) × P(is|its water)

× P(so|its water is) × P(transparent|its water is so)

How to estimate these probabilities

- Could we just count and divide?

$$P(\text{the} \mid \text{its water is so transparent that}) =$$

$$\frac{Count(\text{its water is so transparent that the})}{Count(\text{its water is so transparent that})}$$

How to estimate these probabilities

- Could we just count and divide?

$$P(\text{the} \mid \text{its water is so transparent that}) =$$

$$\frac{Count(\text{its water is so transparent that the})}{Count(\text{its water is so transparent that})}$$

- No! Too many possible sentences!
- We'll never see enough data for estimating these

Markov Assumption

Andrei Markov (1856~1922)

- Simplifying assumption:

$$P(\text{the} \mid \text{its water is so transparent that}) \approx P(\text{the} \mid \text{that})$$

- Or maybe

$$P(\text{the} \mid \text{its water is so transparent that}) \approx P(\text{the} \mid \text{transparent that})$$

Markov Assumption

$$P(w_1 w_2 \ldots w_n) \approx \prod_i P(w_i \mid w_{i-k} \ldots w_{i-1})$$

- In other words, we approximate each component in the product

$$P(w_i \mid w_1 w_2 \ldots w_{i-1}) \approx P(w_i \mid w_{i-k} \ldots w_{i-1})$$

Simplest case: Unigram model

$$P(w_1 w_2 \ldots w_n) \approx \prod_i P(w_i)$$

Some automatically generated sentences from a unigram model:

```
fifth, an, of, futures, the, an, incorporated, a, a,
the, inflation, most, dollars, quarter, in, is, mass

thrift, did, eighty, said, hard, 'm, july, bullish

that, or, limited, the
```

How can we generate text from a language model?

Approximating Shakespeare

1 gram	–To him swallowed confess hear both. Which. Of save on trail for are ay device and rote life have –Hill he late speaks; or! a more to leg less first you enter
2 gram	–Why dost stand forth thy canopy, forsooth; he is this palpable hit the King Henry. Live king. Follow. –What means, sir. I confess she? then all sorts, he is trim, captain.
3 gram	–Fly, and will rid me these news of price. Therefore the sadness of parting, as they say, ’tis done. –This shall forbid it should be branded, if renown made it empty.
4 gram	–King Henry. What! I will go seek the traitor Gloucester. Exeunt some of the watch. A great banquet serv’d in; –It cannot be but so.

N-gram models

- We can extend to trigrams, 4-grams, 5-grams
- In general this is an insufficient model of language
  - because language has **long-distance dependencies**:

“The computer which I had just put into the machine room on the fifth floor crashed.”

Estimating bigram probabilities

- The Maximum Likelihood Estimate (MLE)
  - relative frequency based on the empirical counts on a training set

$$P(w_i \mid w_{i-1}) = \frac{count(w_{i-1}, w_i)}{count(w_{i-1})}$$

$$P(w_i \mid w_{i-1}) = \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

c — count

An example

$$P(w_i \mid w_{i-1}) \overset{\text{MLE}}{=} \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

<s> I am Sam </s>

<s> Sam I am </s>

<s> I do not like green eggs and ham </s>

$P(\texttt{I} \mid \texttt{<s>}) = \frac{2}{3} = .67 \qquad P(\texttt{Sam} \mid \texttt{<s>}) = ???$

$P(\texttt{</s>} \mid \texttt{Sam}) = \frac{1}{2} = 0.5 \qquad P(\texttt{Sam} \mid \texttt{am}) = ???$

An example

$$P(w_i \mid w_{i-1}) \overset{\text{MLE}}{=} \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

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$P(\texttt{I} \mid \texttt{<s>}) = \frac{2}{3} = .67$ $\quad P(\texttt{Sam} \mid \texttt{<s>}) = \frac{1}{3} = .33$ $\quad P(\texttt{am} \mid \texttt{I}) = \frac{2}{3} = .67$

$P(\texttt{</s>} \mid \texttt{Sam}) = \frac{1}{2} = 0.5$ $\quad P(\texttt{Sam} \mid \texttt{am}) = \frac{1}{2} = .5$ $\quad P(\texttt{do} \mid \texttt{I}) = \frac{1}{3} = .33$

Important terminology: a word **type** is a unique word in our vocabulary, while a **token** is an occurrence of a word type in a dataset.

An example

$$P(w_i \mid w_{i-1}) \overset{\text{MLE}}{=} \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

<s> I am Sam </s>
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A bigger example:
Berkeley Restaurant Project sentences

- can you tell me about any good cantonese restaurants close by
- mid priced thai food is what i'm looking for
- tell me about chez panisse
- can you give me a listing of the kinds of food that are available
- i'm looking for a good place to eat breakfast
- when is caffe venezia open during the day

Raw bigram counts

note: this is only a subset of the (much bigger) bigram count table

- Out of 9222 sentences

	i	want	to	eat	chinese	food	lunch	spend
i	5	827	0	9	0	0	0	2
want	2	0	608	1	6	6	5	1
to	2	0	4	686	2	0	6	211
eat	0	0	2	0	16	2	42	0
chinese	1	0	0	0	0	82	1	0
food	15	0	15	0	1	4	0	0
lunch	2	0	0	0	0	1	0	0
spend	1	0	1	0	0	0	0	0

Raw bigram probabilities

$$P(w_i \mid w_{i-1}) \overset{\text{MLE}}{=} \frac{c(w_{i-1}, w_i)}{c(w_{i-1})}$$

- Normalize by unigrams:
- Result:

i	want	to	eat	chinese	food	lunch	spend
2533	927	2417	746	158	1093	341	278

	i	want	to	eat	chinese	food	lunch	spend
i	0.002	0.33	0	0.0036	0	0	0	0.00079
want	0.0022	0	0.66	0.0011	0.0065	0.0065	0.0054	0.0011
to	0.00083	0	0.0017	0.28	0.00083	0	0.0025	0.087
eat	0	0	0.0027	0	0.021	0.0027	0.056	0
chinese	0.0063	0	0	0	0	0.52	0.0063	0
food	0.014	0	0.014	0	0.00092	0.0037	0	0
lunch	0.0059	0	0	0	0	0.0029	0	0
spend	0.0036	0	0.0036	0	0	0	0	0

Bigram estimates of sentence probabilities

P(<s> I want english food </s>) =

P(I|<s>)

× P(want|I)

× P(english|want)

× P(food|english)

× P(</s>|food)

= .000031

these probabilities get super tiny when we have longer inputs w/ more infrequent words… how can we get around this?

logs to avoid underflow

$$\log \prod p(w_i \mid w_{i-1}) = \sum \log p(w_i \mid w_{i-1})$$

Example with unigram model on a sentiment dataset:

logs to avoid underflow

$$\log \prod p(w_i \mid w_{i-1}) = \sum \log p(w_i \mid w_{i-1})$$

Example with unigram model on a sentiment dataset:

$p(\text{i}) \cdot p(\text{love})^5 \cdot p(\text{the}) \cdot p(\text{movie})$ = 5.95374181e-7

$\log p(\text{i}) + 5 \log p(\text{love}) + \log p(\text{the}) + \log p(\text{movie})$

= -14.3340757538

What kinds of knowledge?

- P(english|want) = .0011
- P(chinese|want) = .0065

about the world

- P(to|want) = .66

grammar — infinitive verb

- P(eat | to) = .28
- P(food | to) = 0

???

- P(want | spend) = 0

grammar

- P (i | <s>) = .25

Language Modeling Toolkits

- SRILM
  - http://www.speech.sri.com/projects/srilm/

- KenLM
  - https://kheafield.com/code/kenlm/

Evaluation: How good is our model?

- Does our language model prefer good sentences to bad ones?
  - Assign higher probability to "real" or "frequently observed" sentences
    - Than "ungrammatical" or "rarely observed" sentences?
- We train parameters of our model on a **training set**.
- We test the model's performance on data we haven't seen.
  - A **test set** is an unseen dataset that is different from our training set, totally unused.
  - An **evaluation metric** tells us how well our model does on the test set.

Evaluation: How good is our model?

- The goal isn't to pound out fake sentences!
  - Obviously, generated sentences get "better" as we increase the model order
  - More precisely: using maximum likelihood estimators, higher order is always better likelihood on **training set,** but not **test set**

Example: I use a bunch of New York Times articles to build a bigram probability table

train

	i	want	to	eat	chinese	food	lunch	spend
i	0.002	0.33	0	0.0036	0	0	0	0.00079
want	0.0022	0	0.66	0.0011	0.0065	0.0065	0.0054	0.0011
to	0.00083	0	0.0017	0.28	0.00083	0	0.0025	0.087
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evaluate

Now I'm going to evaluate the probability of some *heldout* data using our bigram table

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evaluate

A good language model should assign a high probability to heldout text!*

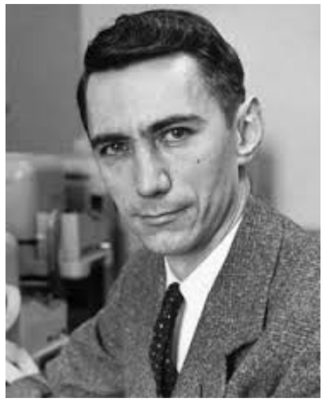
Now I'm going to evaluate the probability of some *heldout* data using our bigram table

Training on the test set

- We can’t allow test sentences into the training set
- We will assign it an artificially high probability when we set it in the test set
- “Training on the test set”
- Bad science!

This advice is generally applicable to any downstream task! Do NOT do this in your final projects unless you want to lose a lot of points :)

Intuition of Perplexity



Claude Shannon
(1916~2001)

- The Shannon Game:
  - How well can we predict the next word?

    I always order pizza with cheese and ____

    The 33rd President of the US was ____

    I saw a ____
  - Unigrams are terrible at this game. (Why?)
- A better model of a text
  - is one which assigns a higher probability to the word that actually occurs

mushrooms 0.1
pepperoni 0.1
anchovies 0.01
….
fried rice 0.0001
….
and 1e-100

Perplexity

The best language model is one that best predicts an unseen test set

- Gives the highest P(sentence)

Perplexity is the inverse probability of the test set, normalized by the number of words:

$$PP(W) = P(w_1 w_2 \ldots w_N)^{-\frac{1}{N}}$$

$$= \sqrt[N]{\frac{1}{P(w_1 w_2 \ldots w_N)}}$$

Chain rule:

$$\mathrm{PP}(W) = \sqrt[N]{\prod_{i=1}^{N} \frac{1}{P(w_i|w_1 \ldots w_{i-1})}}$$

For bigrams:

$$\mathrm{PP}(W) = \sqrt[N]{\prod_{i=1}^{N} \frac{1}{P(w_i|w_{i-1})}}$$

Minimizing perplexity is the same as maximizing probability

Perplexity as branching factor

Let's suppose a sentence consisting of random digits

What is the perplexity of this sentence according to a model that assign P=1/10 to each digit?

$$
\begin{aligned}
\mathrm{PP}(W) &= P(w_1 w_2 \ldots w_N)^{-\frac{1}{N}} \\
&= (\frac{1}{10}^N)^{-\frac{1}{N}} \\
&= \frac{1}{10}^{-1} \\
&= 10
\end{aligned}
$$

In practice, we use log probs

$$PP(W) = \exp\Big(-\frac{1}{N}\sum_{i}^{N} \log p(w_i | w_{<i})\Big)$$

In practice, we use log probs

$$PP(W) = \exp\Big(-\frac{1}{N}\sum_{i}^{N}\log p(w_i \mid w_{<i})\Big)$$

Perplexity is the exponentiated *token-level negative log-likelihood*

Lower perplexity = better model

- Training 38 million words, test 1.5 million words, Wall Street Journal

N-gram Order	Unigram	Bigram	Trigram
Perplexity	962	170	109

Zero probability bigrams

- Bigrams with zero probability
  - mean that we will assign 0 probability to the test set!
- And hence we cannot compute perplexity (can't divide by 0)!

$$PP(W) = P(w_1 w_2 \ldots w_N)^{-\frac{1}{N}}$$

$$= \sqrt[N]{\frac{1}{P(w_1 w_2 \ldots w_N)}}$$

for bigram

$$\mathrm{PP}(W) = \sqrt[N]{\prod_{i=1}^{N} \frac{1}{P(w_i | w_{i-1})}}$$

Q: How do we deal with ngrams of zero probabilities?

Shakespeare as corpus

- N=884,647 tokens, V=29,066
- Shakespeare produced 300,000 bigram types out of V^2= 844 million possible bigrams.
  - So 99.96% of the possible bigrams were never seen (have zero entries in the table)

Zeros

Training set:
... denied the allegations
... denied the reports
... denied the claims
... denied the request

P("offer" | denied the) = 0

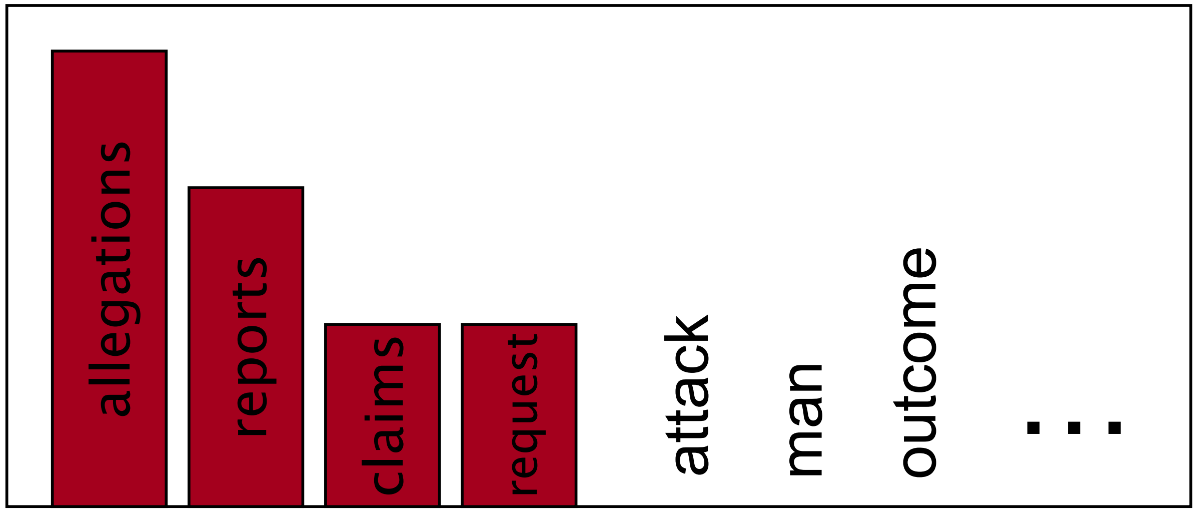
- Test set
  ... denied the offer
  ... denied the loan

The intuition of smoothing (from Dan Klein)

- When we have sparse statistics:

  P(w | denied the)
  3 allegations
  2 reports
  1 claims
  1 request

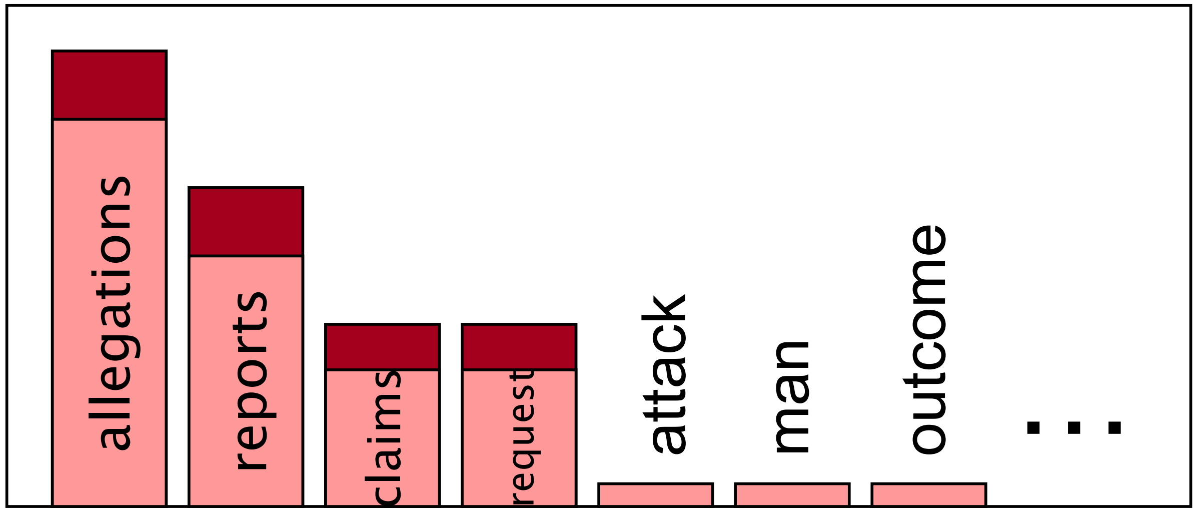
  7 total



- Steal probability mass to generalize better

  P(w | denied the)
  2.5 allegations
  1.5 reports
  0.5 claims
  0.5 request
  2 other

  7 total



Be on the lookout for…

- HW0, due 9/13 on Gradescope
- Final project teams submitted to the Google form by 9/15 (or random assignment)
- Project proposal due 9/24, see Overleaf template
- No quiz this week! Neural LMs next week!