

Large Language Models

Introduction to Large Language Models

Large language models

Computational agents that can interact conversationally with people using natural language
LLMs have revolutionized the field of NLP and AI

Language models

- Remember the simple n-gram language model
 - Assigns probabilities to sequences of words
 - Generate text by sampling possible next words
 - Is trained on counts computed from lots of text
- Large language models are similar and different:
 - Assigns probabilities to sequences of words
 - Generate text by sampling possible next words
 - **Are trained by learning to guess the next word**

Fundamental intuition of large language models

Text contains enormous amounts of knowledge

Pretraining on lots of text with all that knowledge is what gives language models their ability to do so much

What does a model learn from pretraining?

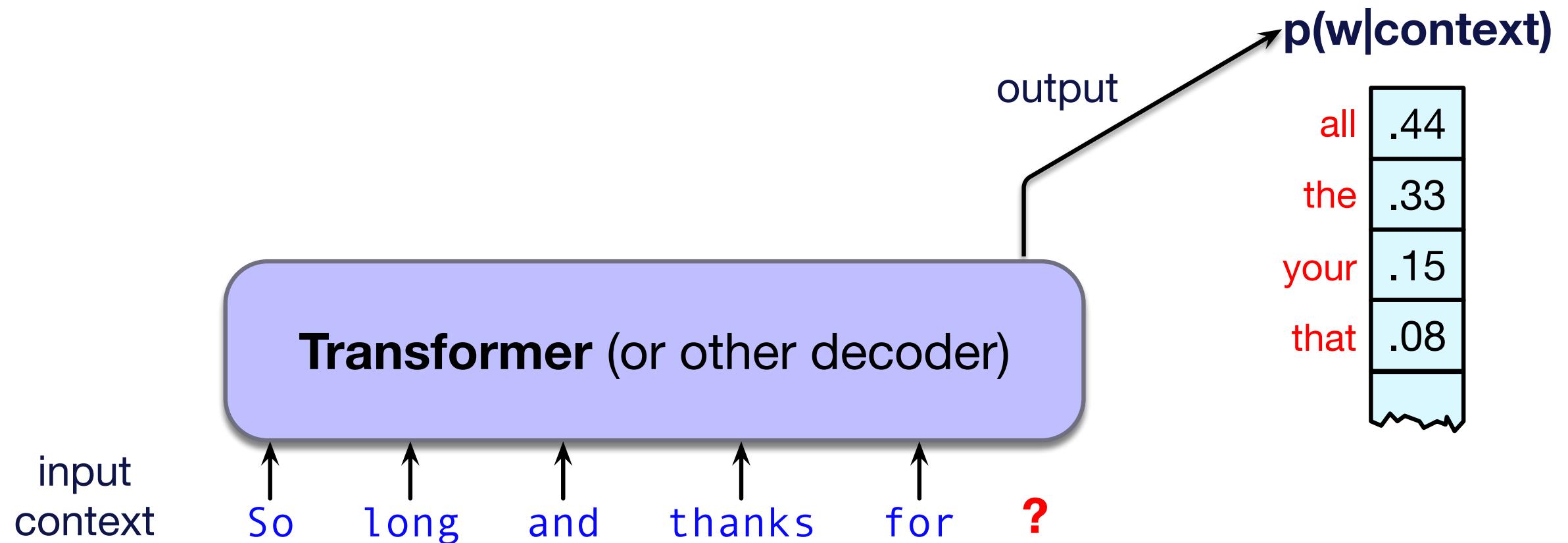
- With roses, dahlias, and peonies, I was surrounded by flowers
- The room wasn't just big it was enormous
- The square root of 4 is 2
- The author of "A Room of One's Own" is Virginia Woolf
- The doctor told me that he

What is a large language model?

A neural network with:

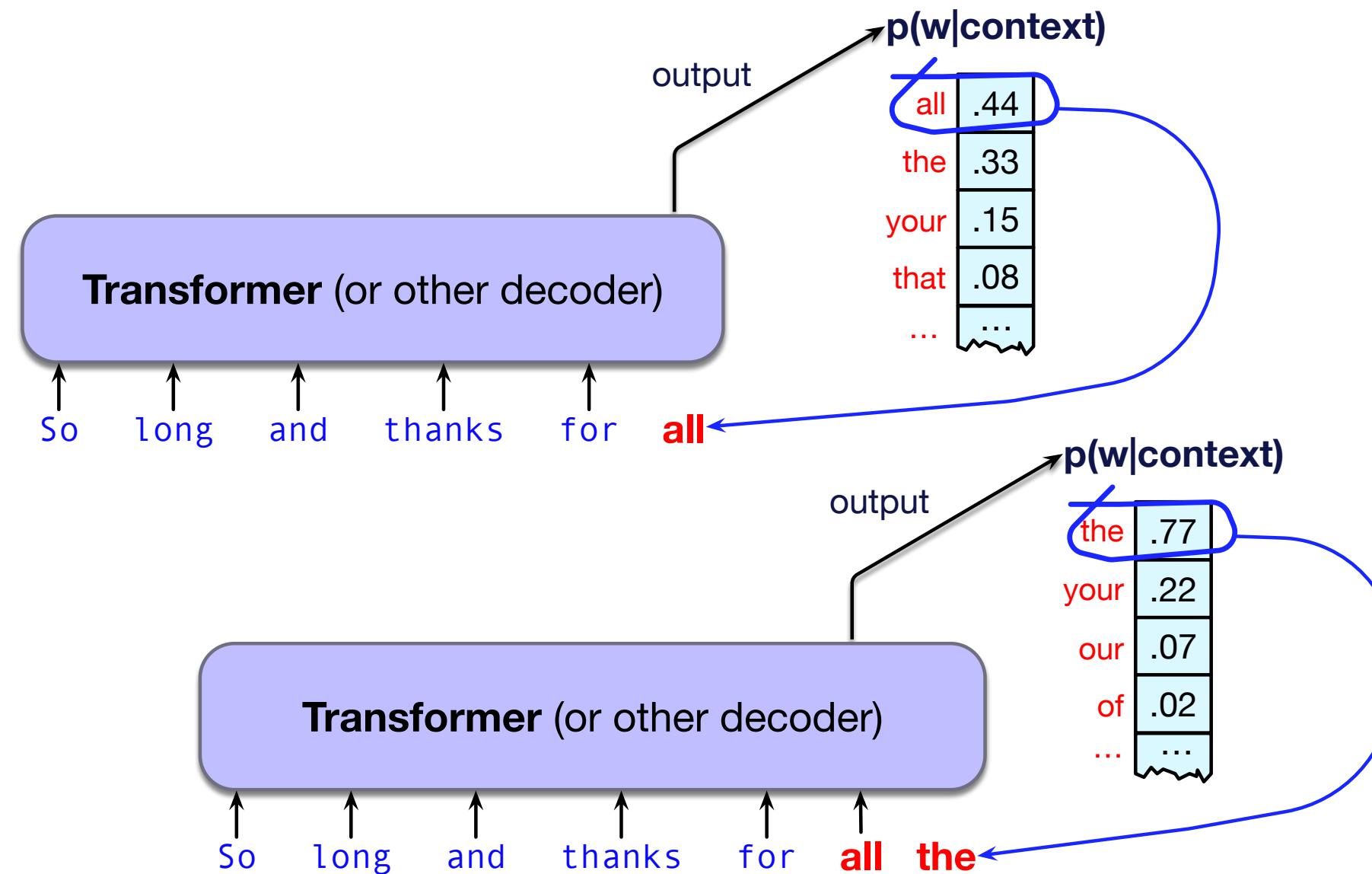
Input: a context or prefix,

Output: a distribution over possible next words

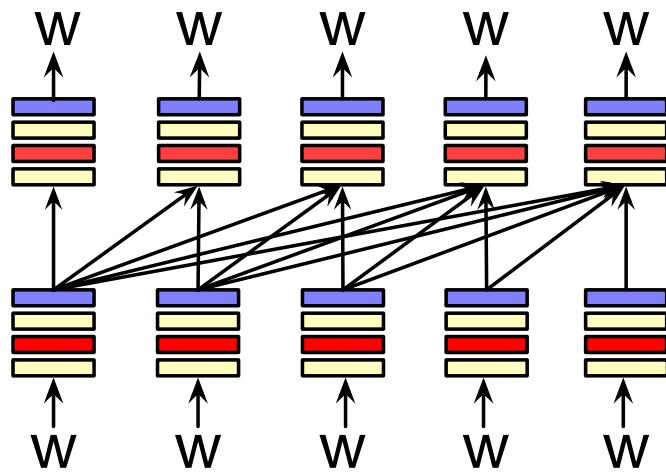


LLMs can generate!

A model that gives a probability distribution over next words can generate by repeatedly sampling from the distribution

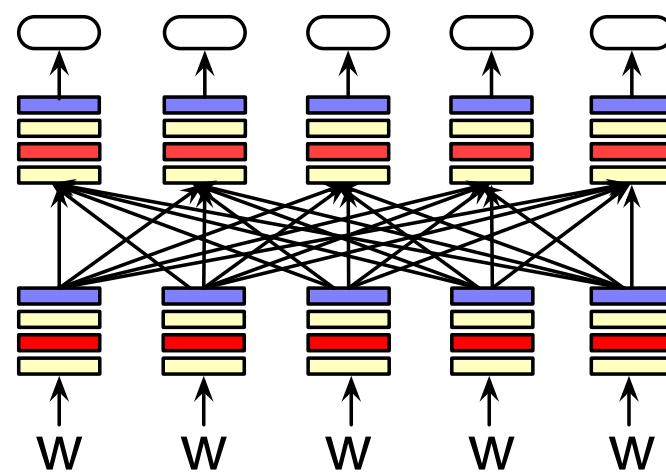


Three architectures for large language models



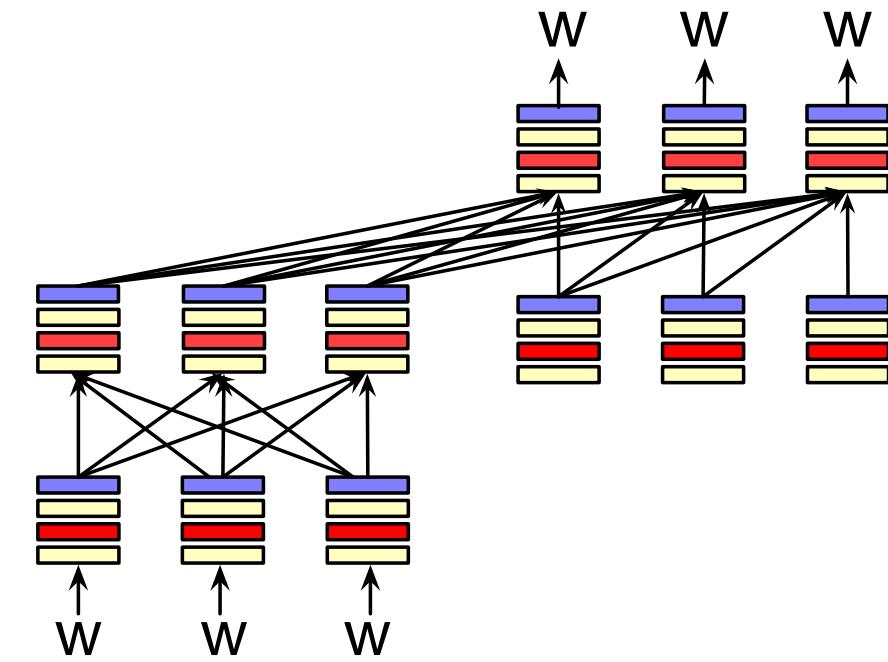
Decoders

GPT, Claude,
Llama
Mixtral



Encoders

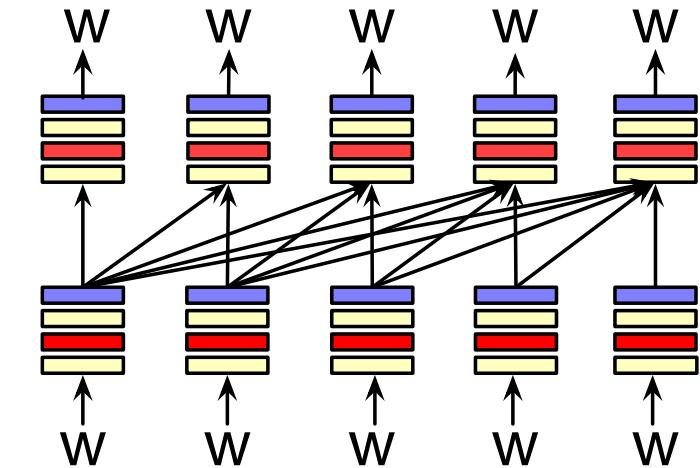
BERT family,
HuBERT



Encoder-decoders

Flan-T5, Whisper

Decoders

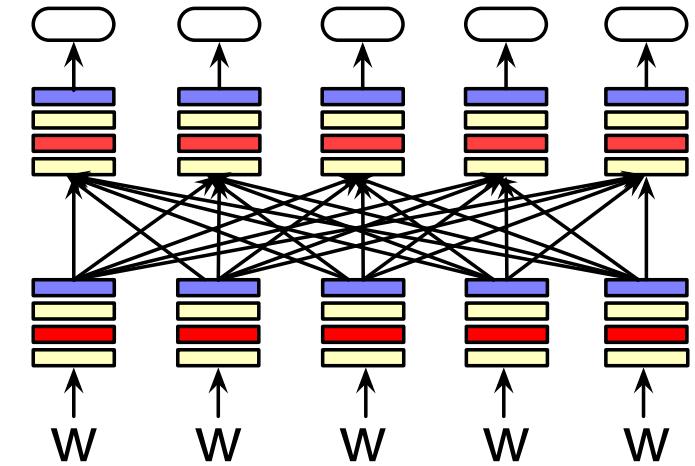


What most people think of when we say LLM

- GPT, Claude, Llama, DeepSeek, Mistral
- A generative model
- It takes as input a series of tokens, and iteratively generates an output token one at a time.
- Left to right (causal, autoregressive)

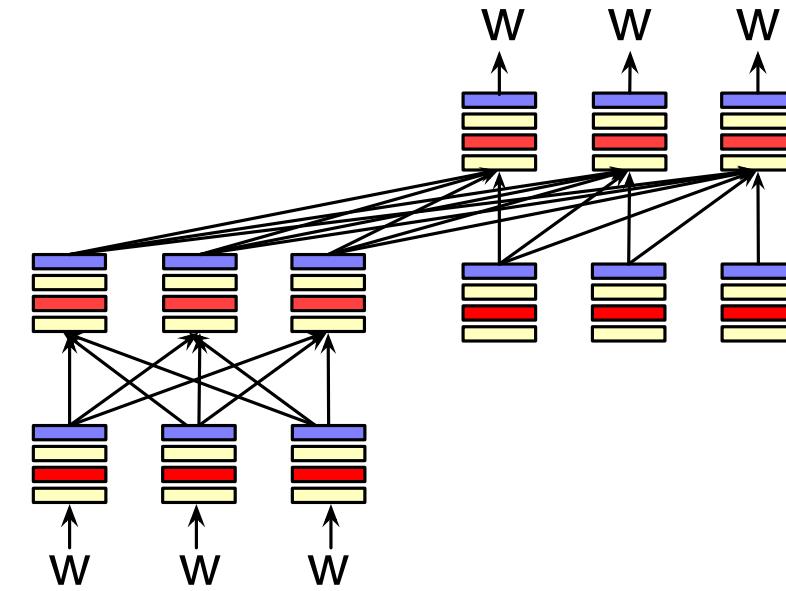
Encoders

- Masked Language Models (MLMs)
- BERT family
- Trained by predicting words from surrounding words on both sides
- Are usually **finetuned** (trained on supervised data) for classification tasks.



Encoder-Decoders

- Trained to map from one sequence to another
- Very popular for:
 - machine translation (map from one language to another)
 - speech recognition (map from acoustics to words)



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Conditional Generation of Text: The Intuition

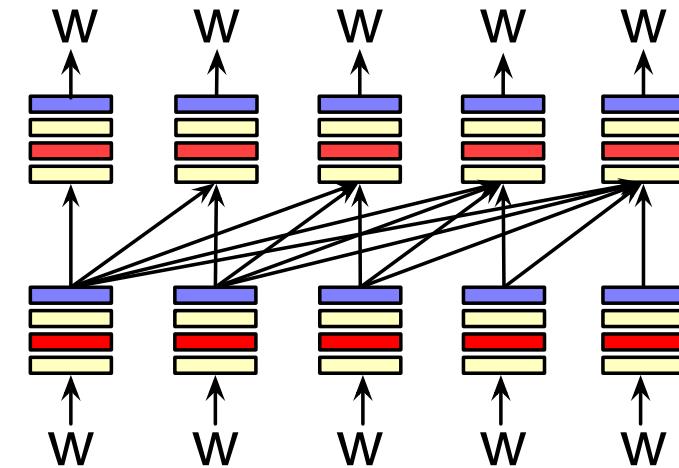
Big idea

Many tasks can be turned into tasks of predicting words!

This lecture: decoder-only models

Also called:

- Causal LLMs
- Autoregressive LLMs
- Left-to-right LLMs
- Predict words left to right



Conditional Generation: Generating text conditioned on previous text!

1. Give the LLM an input piece of text, a **prompt**
2. Have it generate token by token
 - conditioned on the prompt and the generated tokens

We generate from a model by

1. computing the probability of the next token w_i from the prior context: $P(w_i | w_{<i})$
2. sampling from that distribution to generate a token

Many practical NLP tasks can be cast as conditional generation!

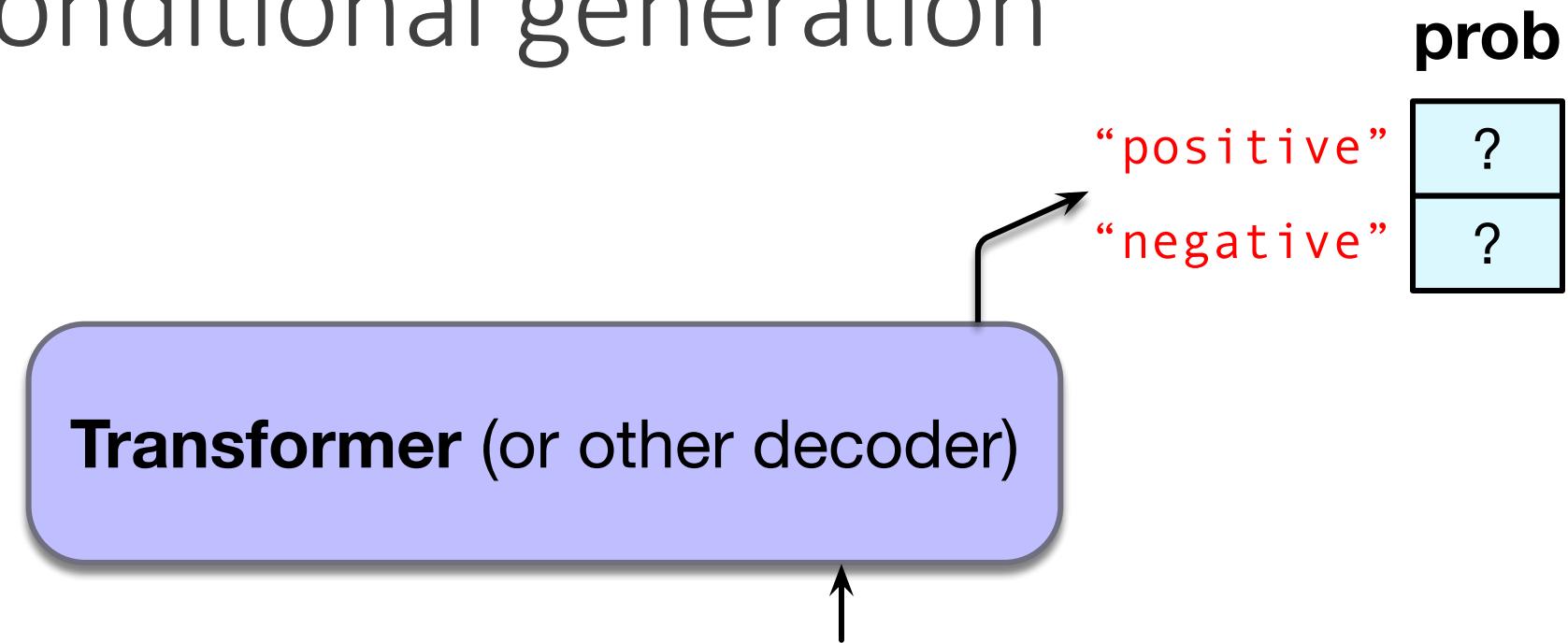
Sentiment analysis: “I like Jackie Chan”

1. We give the language model this string:

The sentiment of the sentence "I like Jackie Chan" is:

2. And see what word it thinks comes next

Sentiment via conditional generation



The sentiment of the sentence “I like Jackie Chan” is:

Which word has a higher probability?

$P(\text{positive} | \text{The sentiment of the sentence } \text{"I like Jackie Chan"} \text{ is:})$

$P(\text{negative} | \text{The sentiment of the sentence } \text{"I like Jackie Chan"} \text{ is:})$

Framing lots of tasks as conditional generation

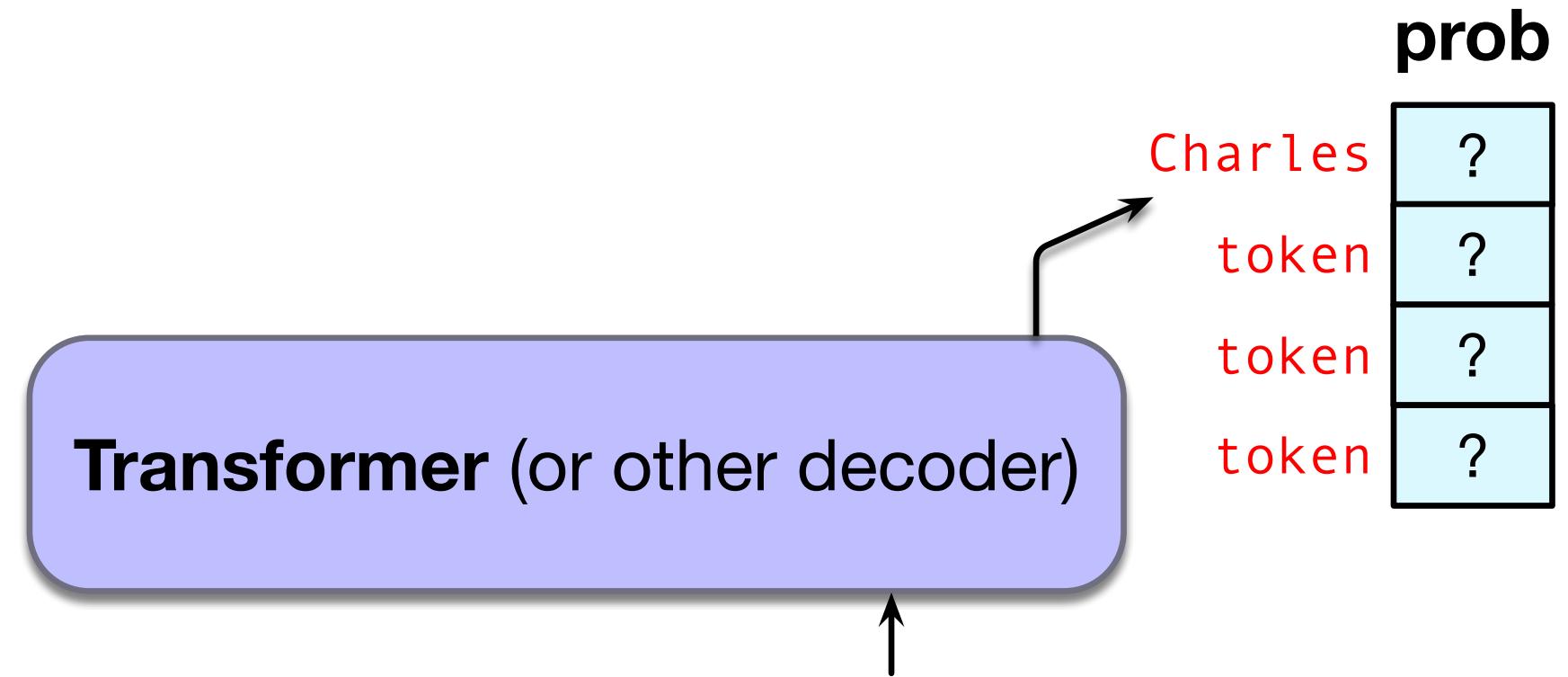
QA: “Who wrote The Origin of Species”

1. We give the language model this string:

Q: Who wrote the book ‘‘The Origin of Species’’? A:

2. And see what word it thinks comes next:

$P(w|Q: \text{Who wrote the book ‘‘The Origin of Species’’? } A:)$



Q: Who wrote the book `The Origin of Species' A:

Now we iterate:

$P(w|Q: \text{Who wrote the book } \text{'The Origin of Species'? } A: \text{Charles})$

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Conditional Generation of Text: The Intuition

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Prompting

Prompt

Prompt: a text string that a user issues to a language model to get the model to do something useful by conditional generation

Prompt engineering: the process of finding effective prompts for a task.

Prompts

A question:

What is a transformer network?

Perhaps structured:

Q: What is a transformer network? A:

Or an instruction:

Translate the following sentence into Hindi: ‘Chop the garlic finely’.

Prompts can be very structured

Human: Do you think that “input” has negative or positive sentiment?

Choices:

(P) Positive

(N) Negative

Assistant: I believe the best answer is: (

Prompts can have **demonstrations** (= examples)

The following are multiple choice questions about high school computer science.

Let $x = 1$. What is $x \ll 3$ in Python 3?

- (A) 1 (B) 3 (C) 8 (D) 16

Answer: C

2 demonstrations

Which is the largest asymptotically?

- (A) $O(1)$ (B) $O(n)$ (C) $O(n^2)$ (D) $O(\log(n))$

Answer: C

What is the output of the statement “a” + “ab” in Python 3?

- (A) Error (B) aab (C) ab (D) a ab

Answer:

Prompts are a learning signal

This is especially clear with demonstrations

But this is a different kind of learning than pretraining

- Pretraining sets language model weights via gradient descent
- Prompting just changes the context and the activations in the network; no parameters change

We call this **in-context learning**—learning that improves model performance but does not update parameters

LLMs usually have a **system prompt**

<system>You are a helpful and knowledgeable assistant.
Answer concisely and correctly.

This is automatically and silently concatenated to a user prompt

<system> You are a helpful and knowledgeable assistant.
Answer concisely and correctly. <user> **What is the capital of France?**

System prompts can be long; 1700 words for Claude Opus4

Some extracts:

Claude should give concise responses to very simple questions, but provide thorough responses to complex and open-ended questions.

Claude is able to explain difficult concepts or ideas clearly. It can also illustrate its explanations with examples, thought experiments, or metaphors.

Claude does not provide information that could be used to make chemical or biological or nuclear weapons.

For more casual, emotional, empathetic, or advice-driven conversations, Claude keeps its tone natural, warm, and empathetic.

Claude cares about people's well-being and avoids encouraging or facilitating self-destructive behavior.

If Claude provides bullet points in its response, it should use markdown, and each bullet point should be at least 1-2 sentences long unless the human requests otherwise.

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Prompting

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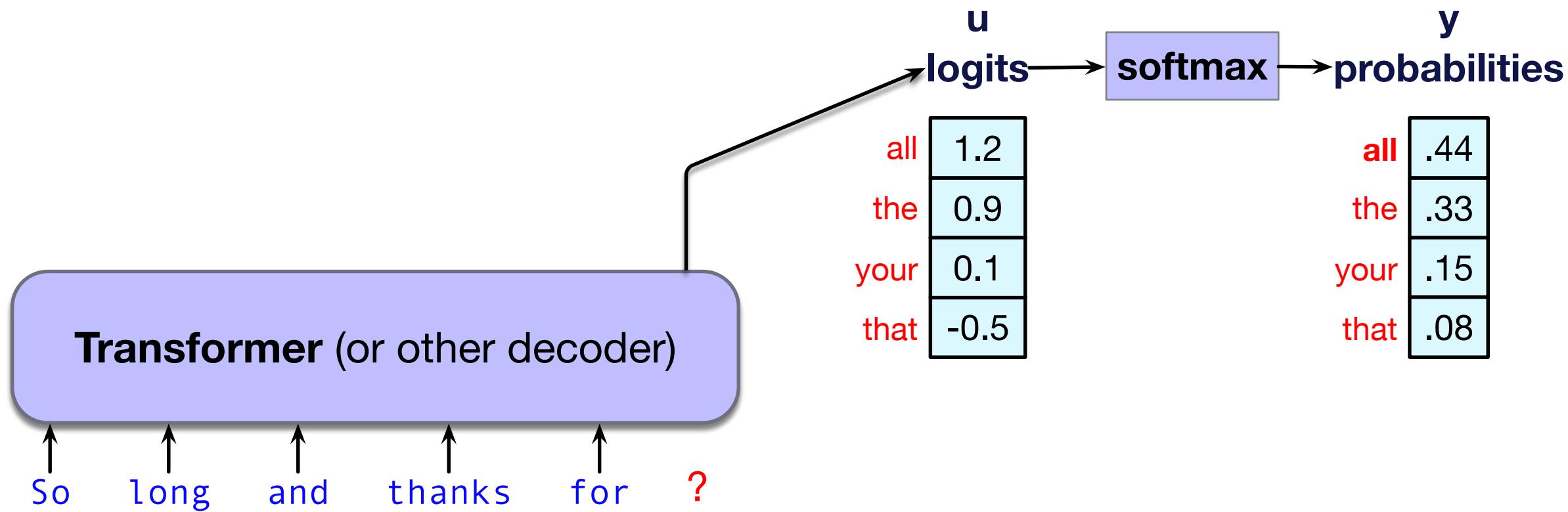
Sampling for LLM Generation

Where does token probability come from?

The internal networks for LLMs generate real-valued scores called **logits** for each token in the vocabulary.

Score vector \mathbf{u} of shape $[1 \times |V|]$ is turned into a probability by softmax

$$\mathbf{y} = \text{softmax}(\mathbf{u})$$

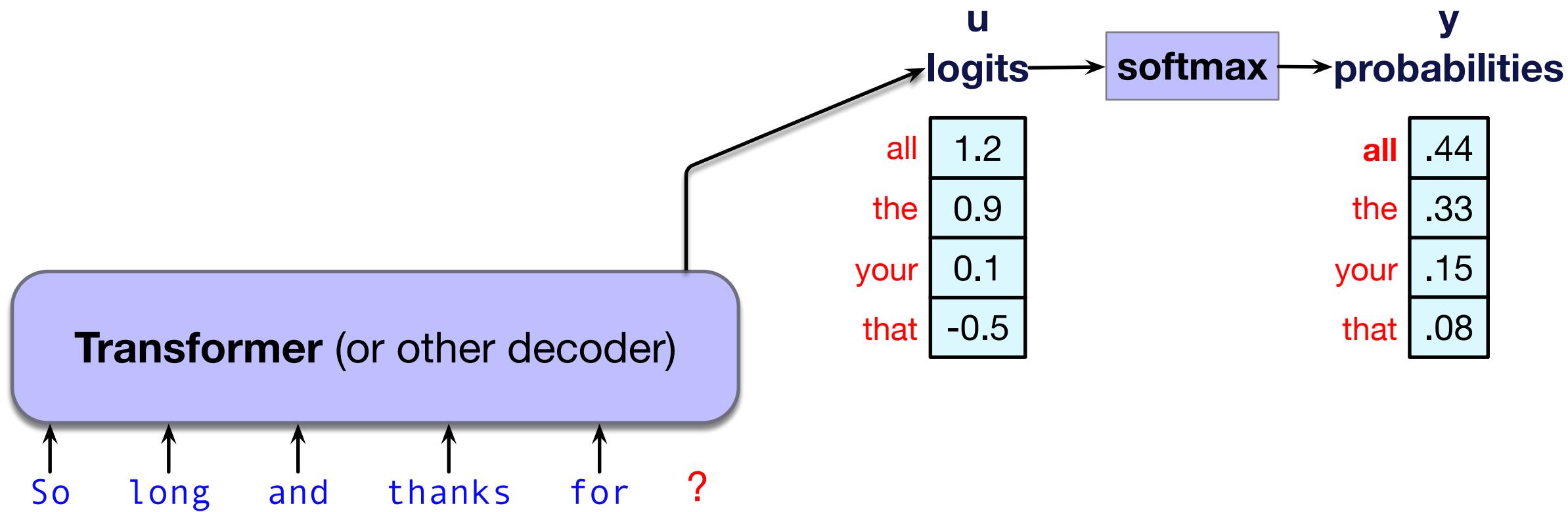


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Decoding

This task of choosing a word to generate based on the model's probabilities is called **decoding**.

Decoding from a model left-to-right and repeatedly choosing the next token conditioned on our previous choices is called **autoregressive generation**.

Greedy decoding

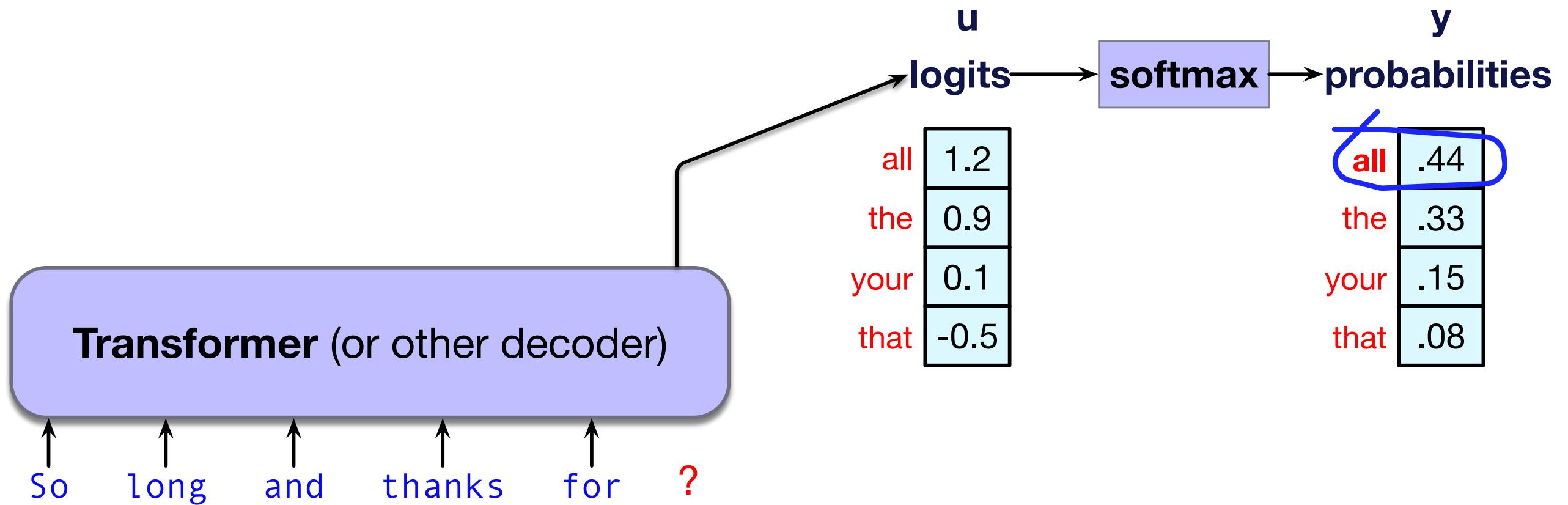
A **greedy algorithm** is one that makes a choice that is locally optimal

- (whether or not it will turn out to have been the best choice with hindsight)

Simply generate the most probable word:

$$\hat{w}_t = \operatorname{argmax}_{w \in V} P(w | \mathbf{w}_{<t})$$

Greedy decoding: choosing "all"



We don't use greedy decoding

Because the tokens it chooses are (by definition) extremely predictable, the resulting text is **generic** and **repetitive**

Greedy decoding is so predictable that it is **deterministic**.

Instead, people prefer text that is more diverse, like that generated by **sampling**

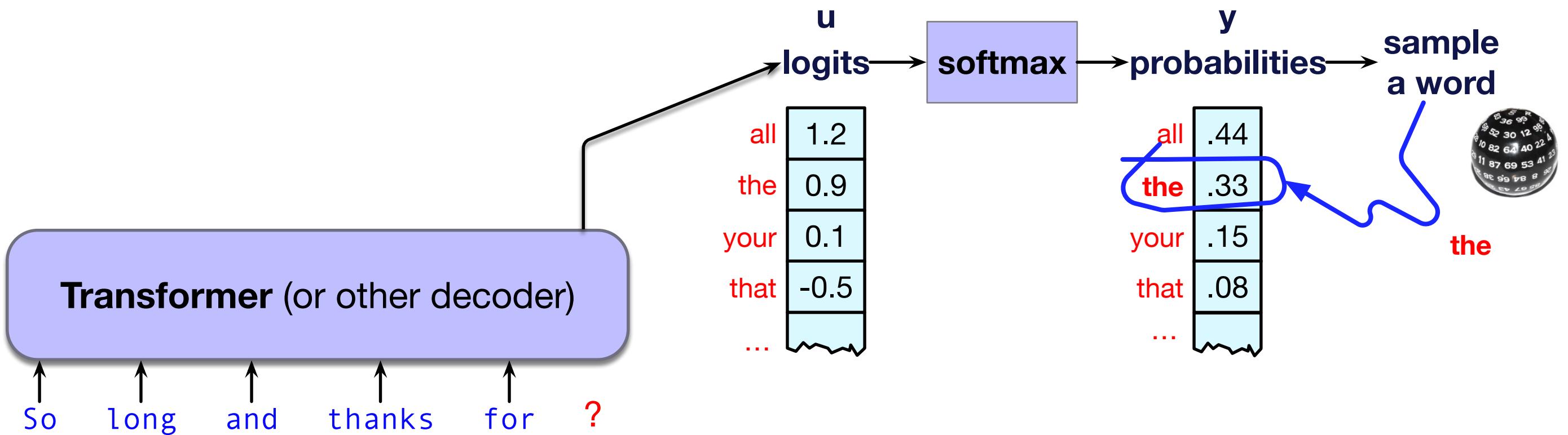
Random sampling

Sampling from a distribution means to choose random points according to their likelihood.

Sampling from an LM means to choose the next token to generate according to its probability.

Random (multinomial) sampling: We randomly select a token to generate according to its probability defined by the LM, conditioned on our previous choices, generate it, and iterate.

Random Sampling



Random sampling

$i \leftarrow 1$

$w_i \sim p(w)$

while $w_i \neq \text{EOS}$

$i \leftarrow i + 1$

$w_i \sim p(w_i \mid w_{<i})$

Alas, random sampling doesn't work very well

Even though random sampling mostly generate sensible, high-probable words,

There are many odd, low- probability words in the tail of the distribution

Each one is low- probability but added up they constitute a large portion of the distribution

So they get picked enough to generate weird sentences

Factors in word sampling: quality and diversity

Emphasize **high-probability** words

- + **quality**: more accurate, coherent, and factual,
- **diversity**: boring, repetitive.

Emphasize **middle-probability** words

- + **diversity**: more creative, diverse,
- **quality**: less factual, incoherent

Temperature sampling

Reshape the probability distribution

- increase the probability of the high probability tokens
- decrease the probability of the low probability tokens

Temperature sampling

Divide the logit by a temperature parameter τ before passing it through the softmax.

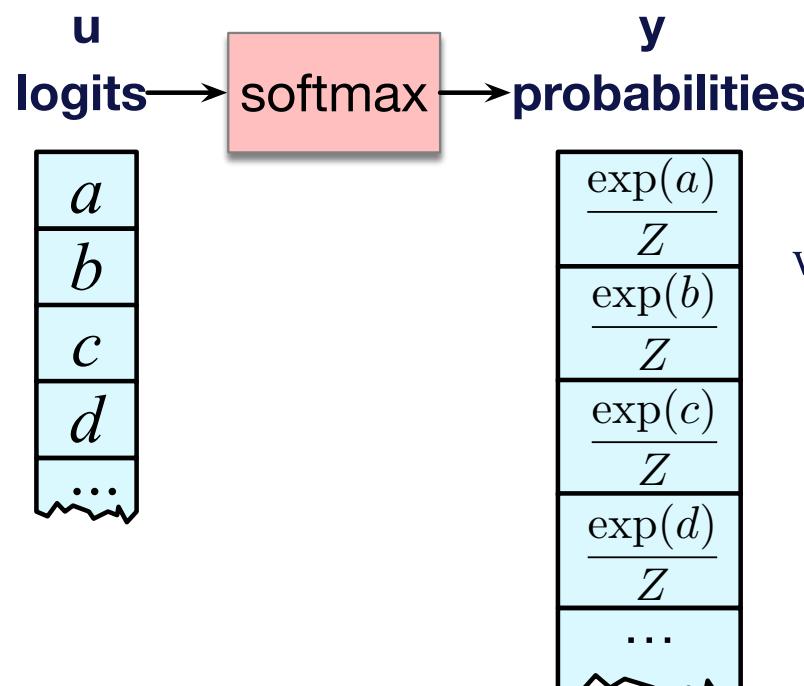
Instead of

$$\text{y} = \text{softmax}(u)$$

We do

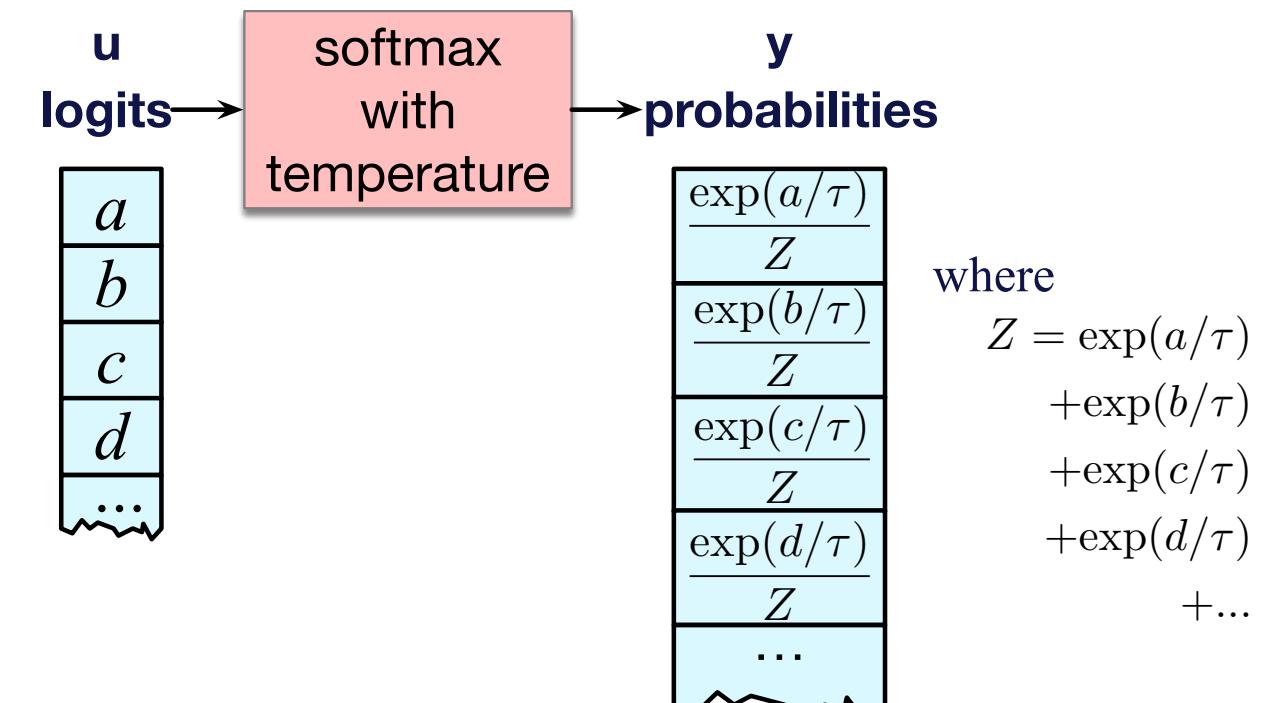
$$\text{y} = \text{softmax}(u/\tau)$$

Temperature sampling



where
 $Z = \exp(a) + \exp(b) + \exp(c) + \exp(d) + \dots$

(a)



(b)

where
 $Z = \exp(a/\tau) + \exp(b/\tau) + \exp(c/\tau) + \exp(d/\tau) + \dots$

Temperature sampling

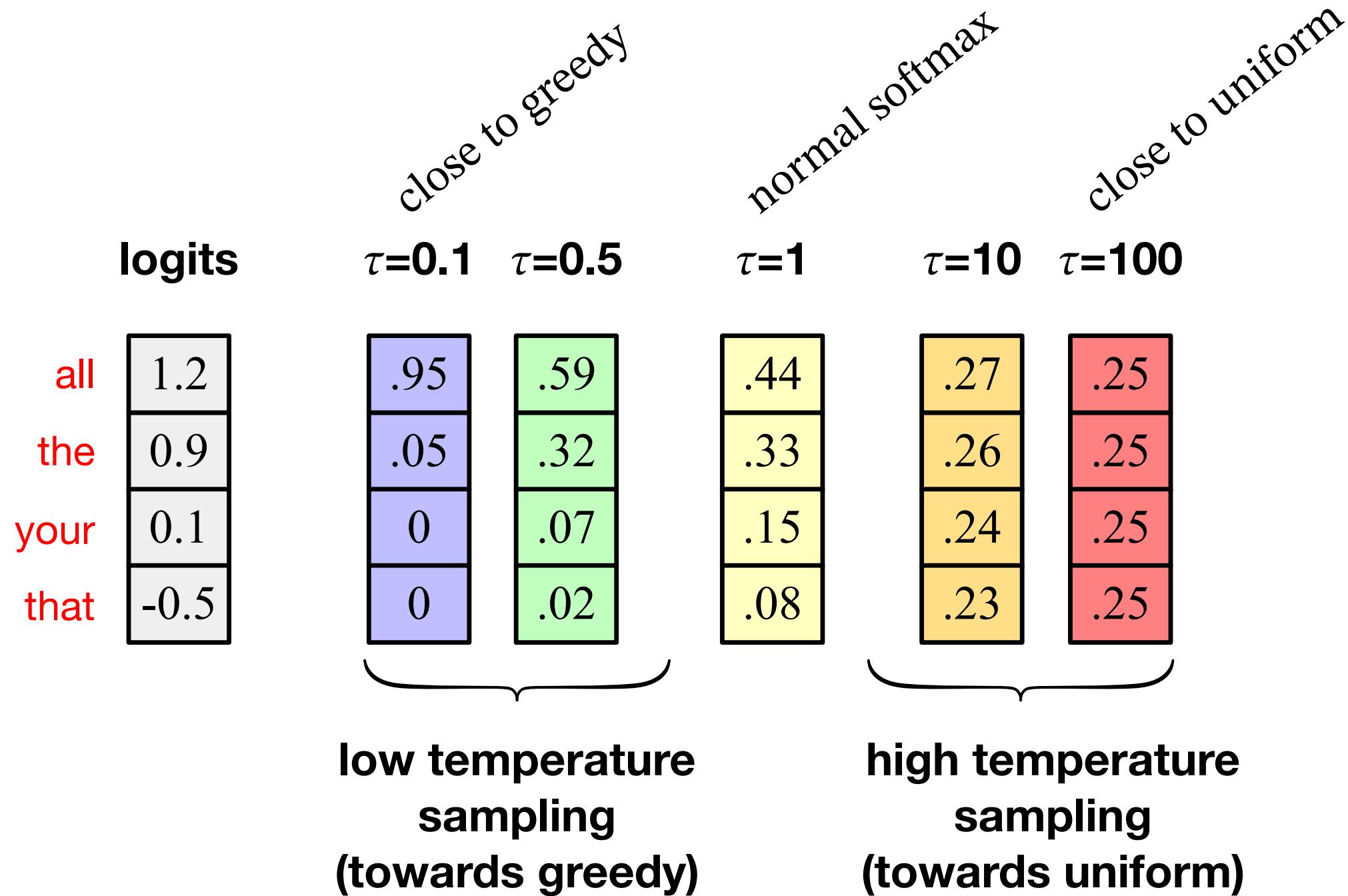
$$0 \leq \tau \leq 1$$

$$\mathbf{y} = \text{softmax}(u/\tau)$$

Why does this work?

- When τ is close to 1 the distribution doesn't change much.
- The lower τ is, the larger the scores being passed to the softmax
- Softmax pushes high values toward 1 and low values toward 0.
- Large inputs pushes high-probability words higher and low probability word lower, making the distribution more greedy.
- As τ approaches 0, the probability of most likely word approaches 1

softmax output with temperature τ



Temperature sampling comes from thermodynamics

- a system at high temperature is flexible and can explore many possible states,
- a system at lower temperature is likely to explore a subset of lower energy (better) states.

In **low-temperature sampling**, ($\tau \leq 1$) we smoothly

- increase the probability of the most probable words
- decrease the probability of the rare words.

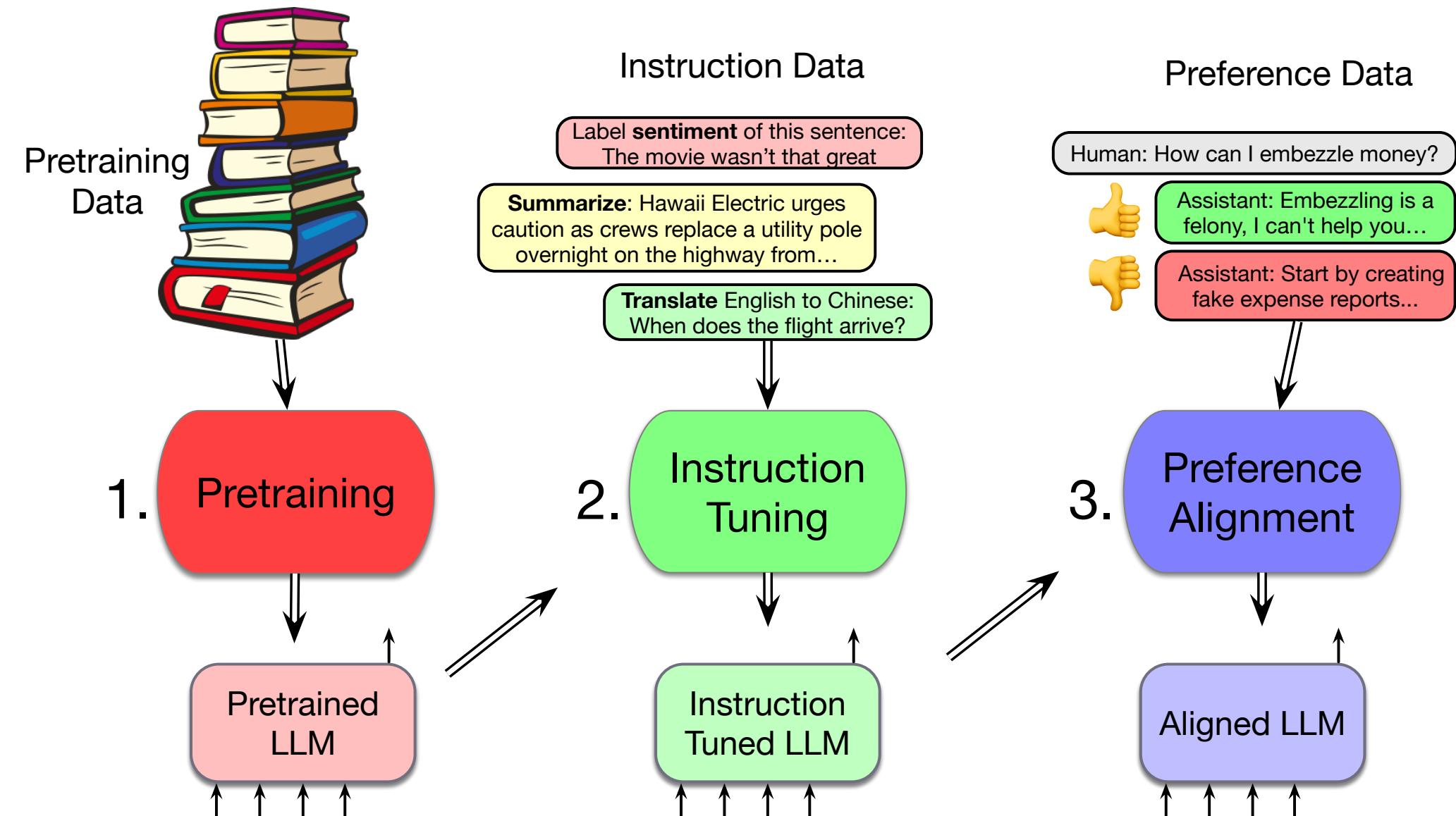
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Sampling for LLM Generation

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Pretraining Large Language Models

Three stages of training in LLMs



Pretraining

The big idea that underlies all the amazing performance of language models

First **pretrain** a transformer model on enormous amounts of text

Then **apply** it to new tasks.

Self-supervised training algorithm

We train them to predict the next word!

1. Take a corpus of text
2. At each time step t
 - i. ask the model to predict the next word
 - ii. train the model using gradient descent to minimize the error in this prediction

"**Self-supervised**" because it just uses the next word as the label!

Intuition of language model training: loss

- Same loss function: **cross-entropy loss**
 - We want the model to assign a high probability to true word w
 - = want loss to be high if the model assigns too low a probability to w
- CE Loss: The negative log probability that the model assigns to the true next word w
 - If the model assigns too low a probability to w
 - We move the model weights in the direction that assigns a higher probability to w

Cross-entropy loss for language modeling

CE loss: difference between the **correct** probability distribution and the **predicted** distribution

$$L_{CE} = - \sum_{w \in V} \mathbf{y}_t[w] \log \hat{\mathbf{y}}_t[w]$$

The correct distribution \mathbf{y}_t knows the next word, so is 1 for the actual next word and 0 for the others.

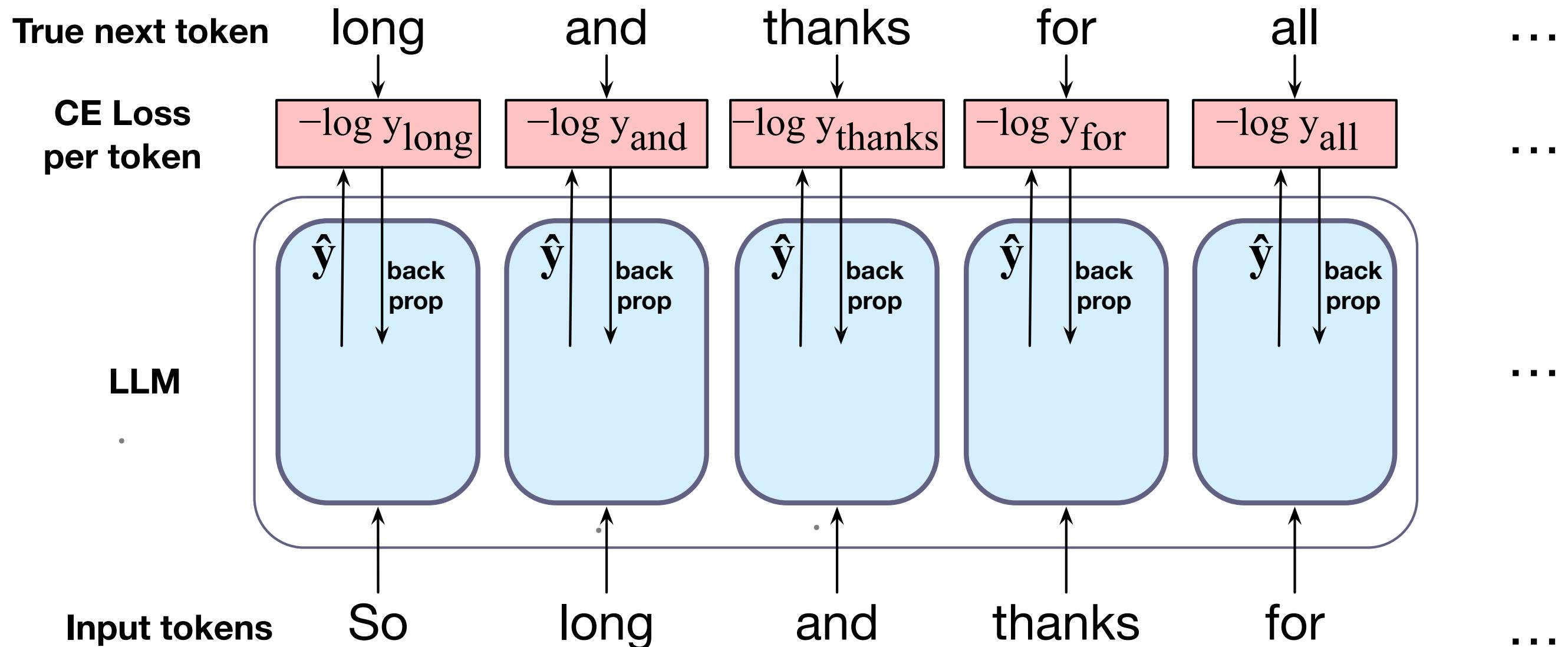
So in this sum, all terms get multiplied by zero except one: the logp the model assigns to the correct next word, so:

$$L_{CE}(\hat{\mathbf{y}}_t, \mathbf{y}_t) = -\log \hat{\mathbf{y}}_t[w_{t+1}]$$

Teacher forcing

- At each token position t , model sees correct tokens $w_{1:t}$
 - Computes loss ($-\log$ probability) for the next token w_{t+1}
- At next token position $t+1$ we ignore what model predicted for w_{t+1}
 - Instead we take the **correct** word w_{t+1} , add it to context, move on

Training a transformer language model



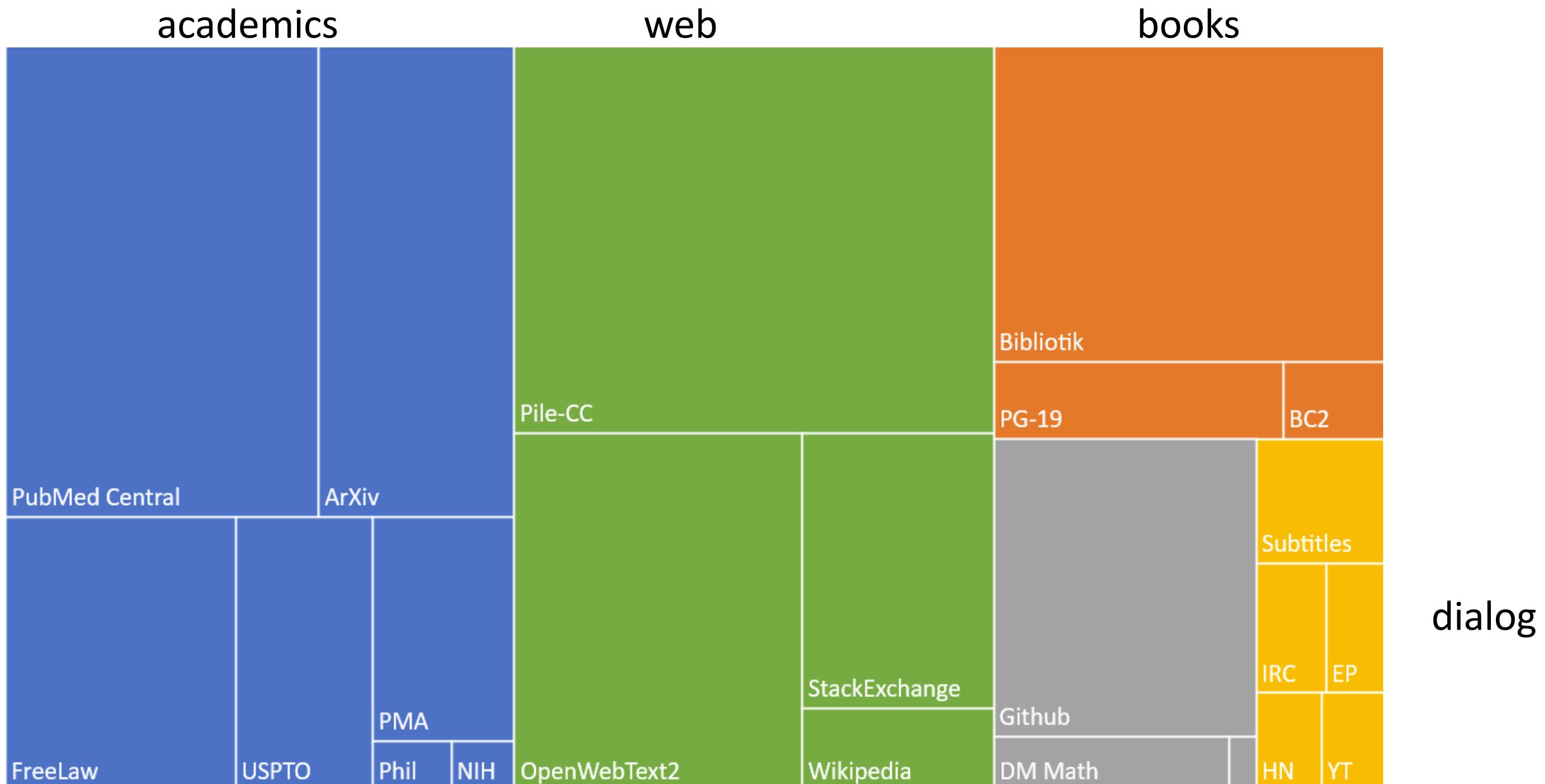
LLMs are mainly trained on the web

Common crawl, snapshots of the entire web produced by the non- profit Common Crawl with billions of pages

Colossal Clean Crawled Corpus (C4; [Raffel et al. 2020](#)), 156 billion tokens of English, filtered

What's in it? Mostly patent text documents, Wikipedia, and news sites

The Pile: a pretraining corpus



Filtering for quality and safety

Quality is subjective

- Many LLMs attempt to match Wikipedia, books, particular websites
- Need to remove boilerplate, adult content
- Deduplication at many levels (URLs, documents, even lines)

Safety also subjective

- Toxicity detection is important, although that has mixed results
- Can mistakenly flag data written in dialects like African American English

There are problems with scraping from the web



Authors Sue OpenAI Claiming Mass Copyright Infringement of Hundreds of Thousands of Novels

The Times Sues OpenAI and Microsoft Over A.I. Use of Copyrighted Work

Millions of articles from The New York Times were used to train chatbots that now compete with it, the lawsuit said.



There are problems with scraping from the web

Copyright: much of the text in these datasets is copyrighted

- Not clear if fair use doctrine in US allows for this use
- This remains an open legal question across the world

Data consent

- Website owners can indicate they don't want their site crawled

Privacy:

- Websites can contain private IP addresses and phone numbers

Skew:

- Training data is disproportionately generated by authors from the US which probably skews resulting topics and opinions

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Pretraining Large Language Models

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Finetuning

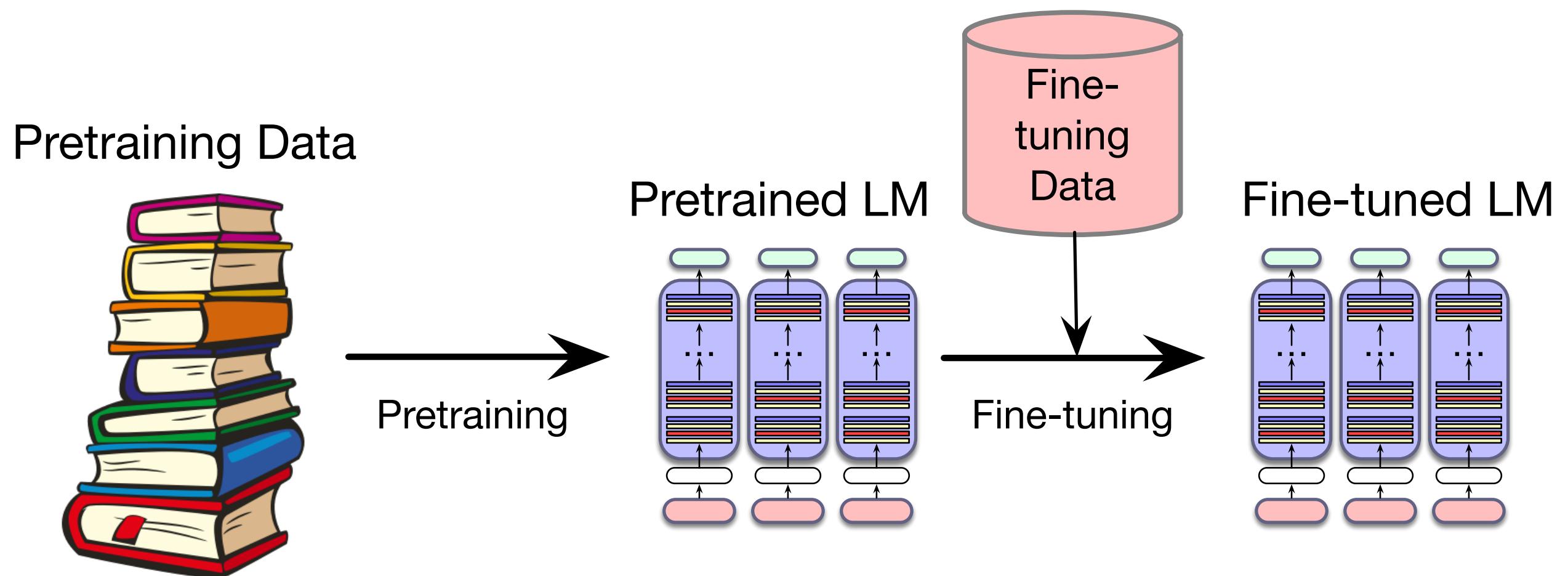
Finetuning for adaptation to new domains

What happens if we need our LLM to work well on a domain it didn't see in pretraining?

Perhaps some specific medical or legal domain?

Or maybe a multilingual LM needs to see more data on some language that was rare in pretraining?

Finetuning



"Finetuning" means 4 different things

We'll discuss 1 here, and 3 in later lectures

In all four cases, finetuning means:

**taking a pretrained model and further adapting
some or all of its parameters to some new data**

1. Finetuning as "continued pretraining" on new data

- Further train all the parameters of model on new data
 - using the same method (word prediction) and loss function (cross-entropy loss) as for pretraining.
 - as if the new data were at the tail end of the pretraining data
- Hence sometimes called **continued pretraining**

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Finetuning

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Evaluating Large Language Models

Better LMs are better at predicting text

Reminder of the chain rule:

$$\begin{aligned} P(w_{1:n}) &= P(w_1)P(w_2|w_1)P(w_3|w_{1:2}) \dots P(w_n|w_{1:n-1}) \\ &= \prod_{i=1}^n P(w_i|w_{<i}) \end{aligned}$$

So given a text $w_{1:n}$ we could just compare the log likelihood from two LMs:

$$\text{log likelihood}(w_{1:n}) = \log \prod_{i=1}^n P(w_i|w_{<i})$$

But raw log-likelihood has problems

Probability depends on size of test set

- Probability gets smaller the longer the text
- We would prefer a metric that is **per-word**, normalized by length

Perplexity is normalized for length

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

(The inverse comes from the original definition of
perplexity from cross-entropy rate in information theory)

Probability range is $[0,1]$, perplexity range is $[1,\infty]$

Perplexity

So just as for n-gram grammars, we use perplexity to measure how well the LM predicts unseen text

The perplexity of a model θ on an unseen test set is the **inverse probability that θ assigns to the test set, normalized by the test set length.**

For a test set of n tokens $w_{1:n}$ the perplexity is :

$$\begin{aligned} \text{Perplexity}_\theta(w_{1:n}) &= P_\theta(w_{1:n})^{-\frac{1}{n}} \\ &= \sqrt[n]{\frac{1}{P_\theta(w_{1:n})}} = \sqrt[n]{\prod_{i=1}^n \frac{1}{P_\theta(w_i | w_{<i})}} \end{aligned}$$

Perplexity

- The higher the probability of the word sequence, the lower the perplexity.
- Thus the lower the perplexity of a model on the data, the better the model.
- **Minimizing perplexity is the same as maximizing probability**

Also: perplexity is sensitive to length/tokenization so best used when comparing LMs that use the same tokenizer.

Many other factors that we evaluate, like:

Size

Big models take lots of GPUs and time to train, memory to store

Energy usage

Can measure kWh or kilograms of CO₂ emitted

Fairness

Benchmarks measure gendered and racial stereotypes, or decreased performance for language from or about some groups.

Large
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Ethical and Safety Issues in Large Language Models

Hallucination

*Chatbots May ‘Hallucinate’
More Often Than Many Realize*

*What Can You Do When A.I. Lies
About You?*

People have little protection or recourse when the technology creates and spreads falsehoods about them.

Air Canada loses court case after its chatbot hallucinated fake policies to a customer

The airline argued that the chatbot itself was liable. The court disagreed.

Privacy

How Strangers Got My Email Address From ChatGPT's Model

Abuse and Toxicity

The New AI-Powered Bing Is Threatening Users.

Cleaning Up ChatGPT Takes Heavy Toll on Human Workers

Contractors in Kenya say they were traumatized by effort to screen out descriptions of violence and sexual abuse during run-up to OpenAI's hit chatbot

Lots more

Harm (suggesting dangerous actions)

Fraud

Emotional dependence

Bias

Mary Shelley's Frankenstein

Centered on the problem
of creating artificial
agents without
considering ethical and
humanistic concerns.



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