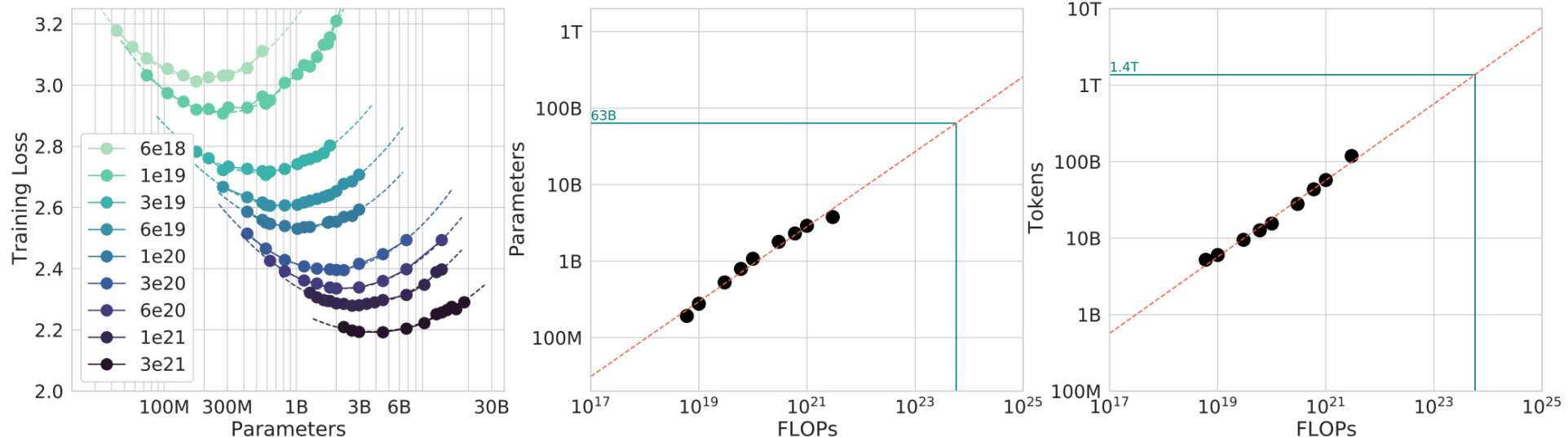


# **Course 5: Language Models at Inference Time**

# Introduction

# Background

Scaling language models (LMs) is the go-to solution to achieve greater performance [1].



# Background

- The more you scale, the more compute you need at inference.
- Hardware costs can hinder LLMs if no optimization is done.
- Not all optimization techniques are born equal...

**What are the different responses to the trade-off between an LLM performance and an LLM throughput?**

# Content

## 1. More About Throughput?

- a. Prompt pruning, when KV caching is not enough
- b. Speculative decoding
- c. Layer skip: self speculative decoding

## 2. More About Performance?

- a. Retrieval augmented generation (at inference)
- b. Test-time compute

## 3. More About "Balance"?

- a. Mixture of experts

# More About Throughput?

# Prompt pruning: when KV caching is not enough

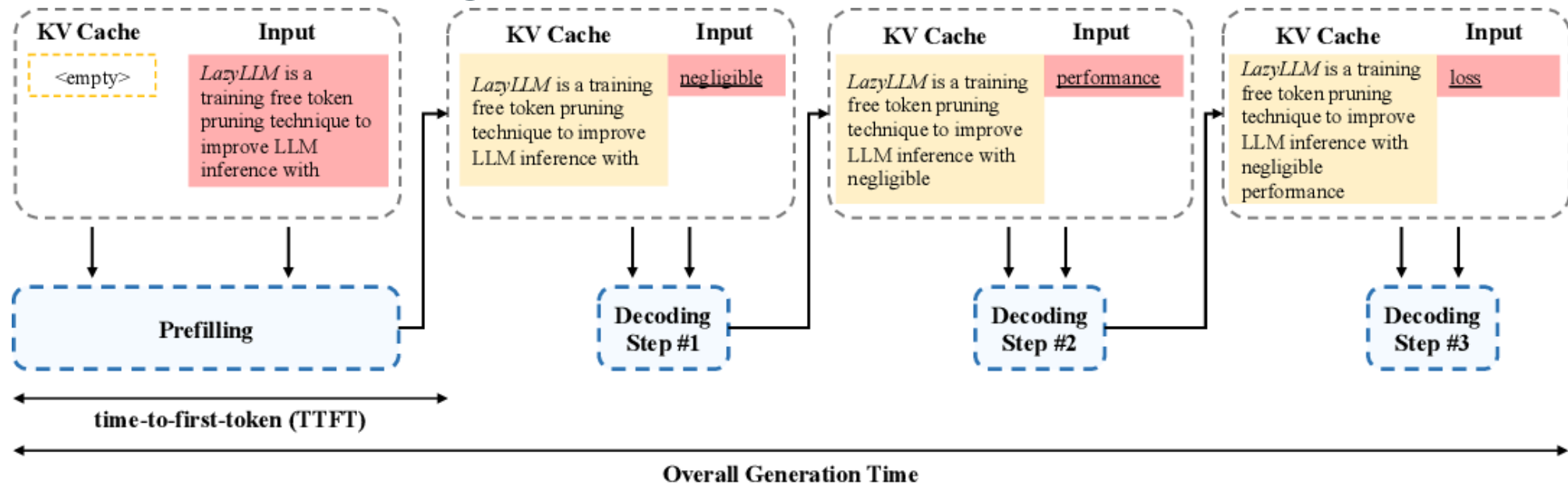
Attention matrices need to be calculated for every token constituting an LLM's prompt, leading to latency.

- On LLaMa2-70b models, given a long prompt, 23% of the total generation time is accounted for the time to first token (TTFT).
- KV caching is of no-use in that context...

How to reduce that TTFT with minimum performance loss?

# Prompt pruning: when KV caching is not enough

When does KV caching comes into play?



The above example assume that your model is aware of LazyLLM [2] via its training data.



# Prompt pruning: when KV caching is not enough

Not all tokens are useful to understand/answer the prompt.

			Accumulated # of Token Computed
LLM	Iteration #1 (Prefilling)	LazyLLM is a training free token pruning technique to improve LLM inference with negligible	13
	Iteration #2	LazyLLM is a training free token pruning technique to improve LLM inference with negligible performance	14
	Iteration #3	LazyLLM is a training free token pruning technique to improve LLM inference with negligible performance loss	15
-----			
LazyLLM	Iteration #1 (Prefilling)	LazyLLM is a training free token pruning technique to improve LLM inference with negligible	4
	Iteration #2	LazyLLM is a training free token pruning technique to improve LLM inference with negligible performance	6
	Iteration #3	LazyLLM is a training free token pruning technique to improve LLM inference with negligible performance loss	7

# Prompt pruning: when KV caching is not enough

How to effectively choose tokens to prune out?

Transformer's attention represents more abstract concept as the computation is done deeper in its layers [3].

The last attention matrices play an important role in the decision boundaries computed by a transformer-based LM [4].

# Prompt pruning: when KV caching is not enough

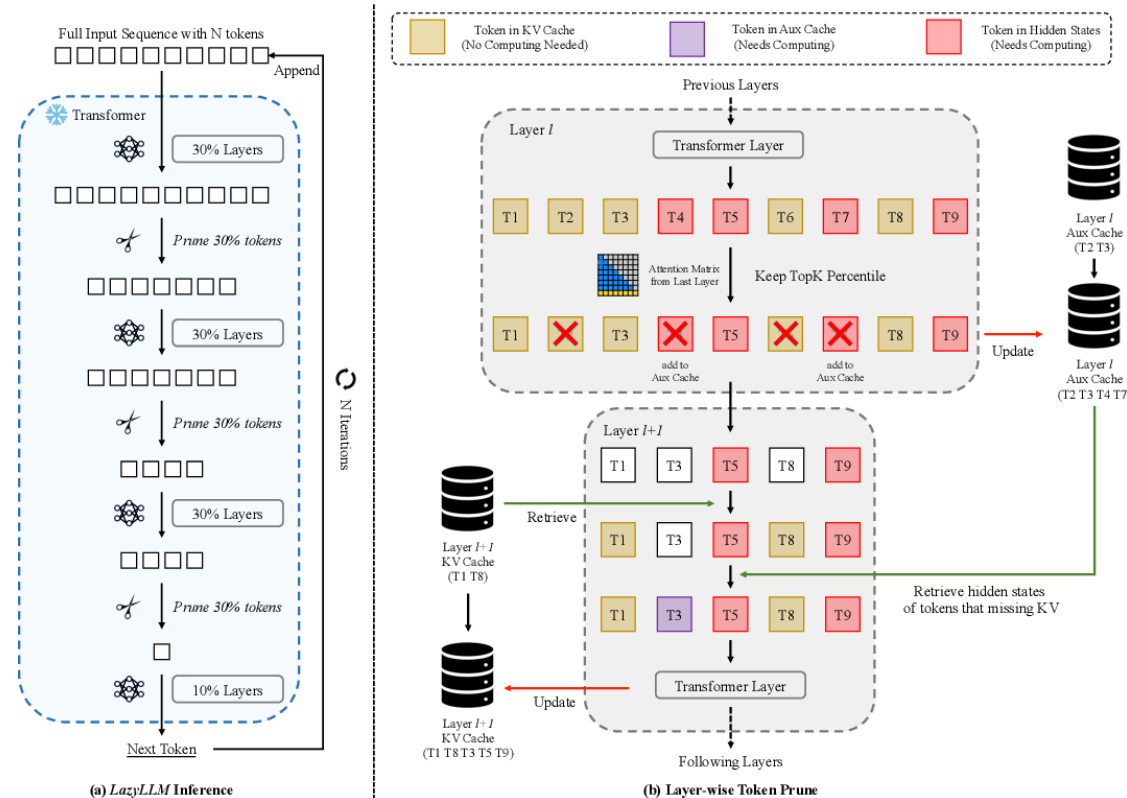
For a given token  $i$ , the attention matrix compute the probability of a token  $j \leq N$  attending to  $i$  accross all  $H$  attention heads of a model. This process is repeated accross the  $l \leq L$  layers of a model.

The importance of an input token  $i$ , at a given layer  $l$  can now be computed as

$$s_i^l = \frac{1}{H} \sum_{h=1}^H \sum_{j=1}^N A_{h,i,j}^l$$

# Prompt pruning: when KV caching is not enough

We do not want to have too few tokens and some of them can become relevant later in the decoding process



# Prompt pruning: when KV caching is not enough

Drawbacks:

- Marginal gain in performance with relatively short prompts.
- Drop in performance in code completion (no stop-words to drop?).

# Speculative decoding

An **LLM** can **predict multiple tokens in a single forward pass** :

- **Speculative decoding** [5] allows an LLM to "**guess**" future tokens while generating current tokens, **all within a single forward pass**.
- By running a draft model to predict multiple tokens, the main model (larger) only has to verify the predicted tokens for "correctness".

# Speculative decoding

1. **Prefix:** [BOS]
2. **Assistant:** [BOS] The quick brown sock jumps
3. **Main:** [BOS] The quick brown fox / sock jumps
4. **Assistant:** [BOS] The quick brown fox jumps over the crazy dog
5. **Main:** The quick brown jumps over the lazy / crazy dog
6. ...

# Speculative decoding

The main model just verifies that the distribution  $q(x)$ , computed by the assistant is not too far from the distribution  $p(x)$  it computes within a forward pass.

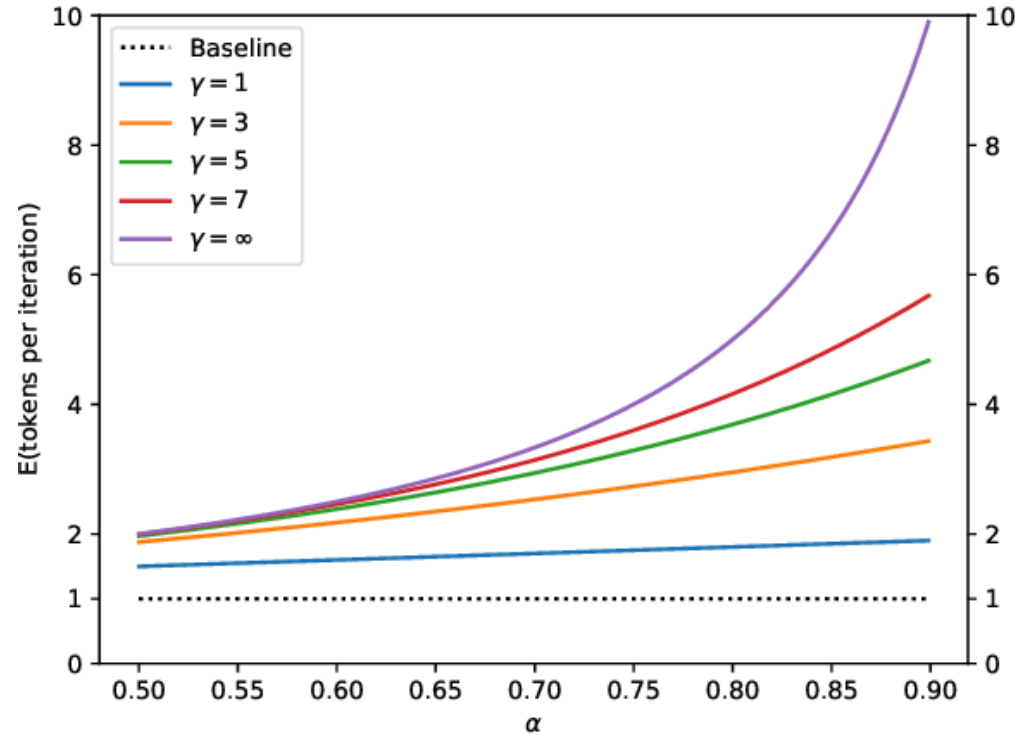
The expected number of tokens generated within one loop of speculative decoding can be theoretically formulated as:

$$E(\#generated\_tokens) = \frac{1 - \alpha^{\gamma+1}}{1 - \alpha}$$

Which is the forward passes' reduction factor.



# Speculative decoding



The expected number of tokens generated via speculative decoding as a function of  $\alpha$  for various values of  $\gamma$ .

# Speculative decoding

In order **to take the most out of speculative decoding**, the distance between  $q(x)$  and  $p(x)$  **needs to be minimal**.

How to reduce the distance between  $q(x)$  and  $p(x)$  when the assistance model is smaller?

- Quantization
- Distillation
- Over-training on the same dataset as the main model

# Layer skip: self speculative decoding

Speculative decoding comes with two inconveniences:

- Loading two models in memory
- Making sure the assistant model outputs a token distribution as close as possible to the main model

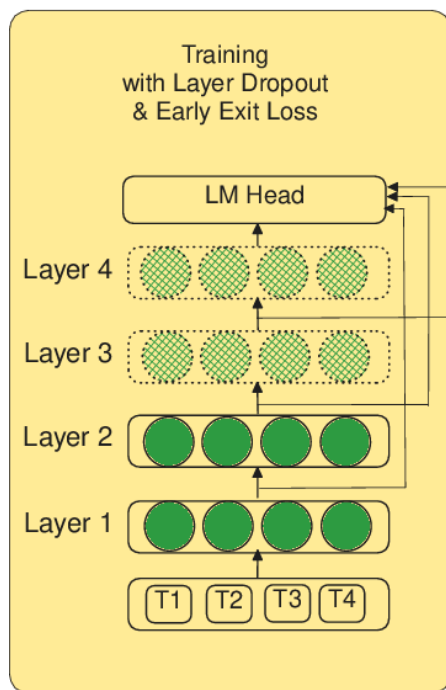
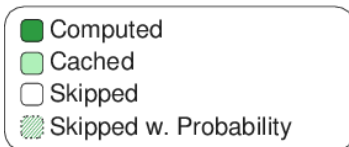
# Layer skip: self speculative decoding

Why not let the main model do the speculation itself?

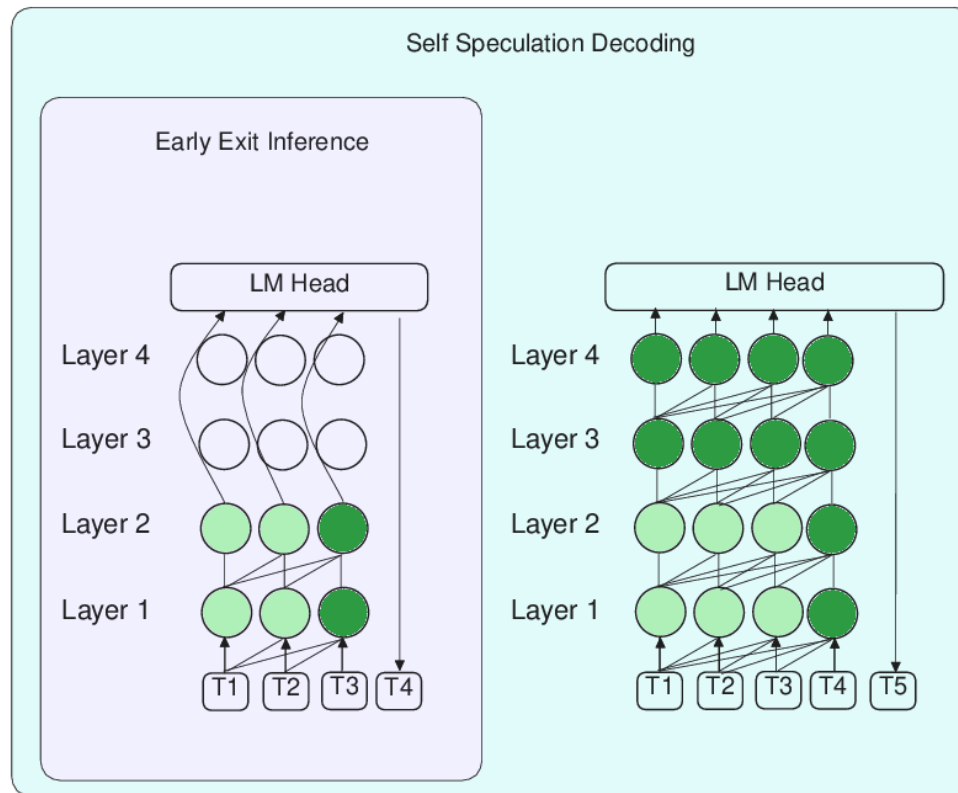
**Transformer models** are believed to be **over-parameterized** and the **last layers specialized** on computing the decision boundaries **before projecting on the LM head**. Maybe we can make **each layer able to project on the LM head**, thus skipping layers [6] and allowing for an **early exit** at inference [7].

# Layer skip: self speculative decoding

Legend



Train using Layer Dropout + Early Exit Loss....



... enables inference with subset of layers with higher accuracy...

... and we can improve accuracy by verifying and correcting with remaining layers

# Layer skip: self speculative decoding

The hidden state of a token  $t$ , at layer  $l + 1$  is stochastically given by

$$x_{l+1,t} = x_{l,t} + M(p_{l,t}) \times f_l(x_{l,t})$$

Where  $M$  is a masking function with a probability of skipping

$$p_{l,t} = S(t) \times D(l) \times p_{max}$$

$$D(l) = e^{\frac{l \times \ln(2)}{L-1}}$$

$$S(t) = e^{\frac{t \times \ln(2)}{T-1}}$$

# Layer skip: self speculative decoding

How is the loss computed?

$$\mathcal{L}_{total} = \sum_{l=0}^{l=L-1} \tilde{e}(t, l) \times \mathcal{L}_{CE}$$

Where  $\tilde{e}(t, l)$  is a normalized per-layer loss scale

$$\tilde{e}(t, l) = \frac{C(t, l) \times e(l)}{\sum_{i=0}^{i=L+1} C(t, i) \times e(i)}$$

# Layer skip: self speculative decoding

$$C(t, l) = \begin{cases} 1 & \text{if there is no early exit at layer } l \\ 0 & \text{otherwise} \end{cases}$$

$e$  is a scale that increases across layers, penalizing later layers, as predicting in later layers is easier.

$$e(l) = \begin{cases} \sum_{i=0}^{i=l} i & \text{if } 0 \leq l \leq L - 1 \\ L - 1 + \sum_{i=0}^{i=L-2} i & \text{if } l = L - 1 \end{cases}$$



# Layer skip: self speculative decoding

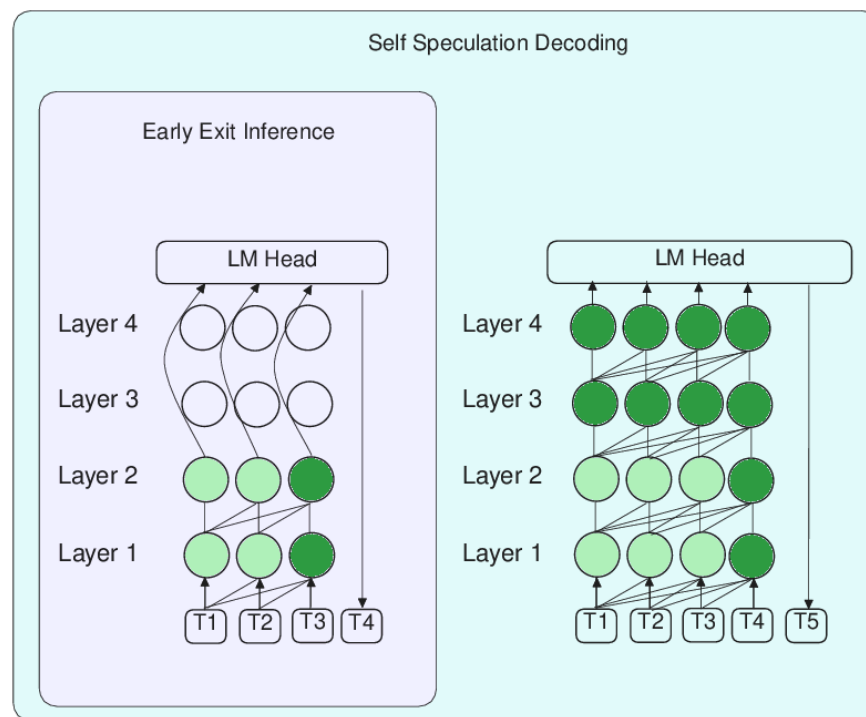
How does this change inference?

Legend

- Computed
- Cached
- Skipped
- ▨ Skipped w. Probability



Train using Layer Dropout + Early Exit Loss....



... enables inference with subset of layers with higher accuracy...

... and we can improve accuracy by verifying and correcting with remaining layers

More About Throughput?

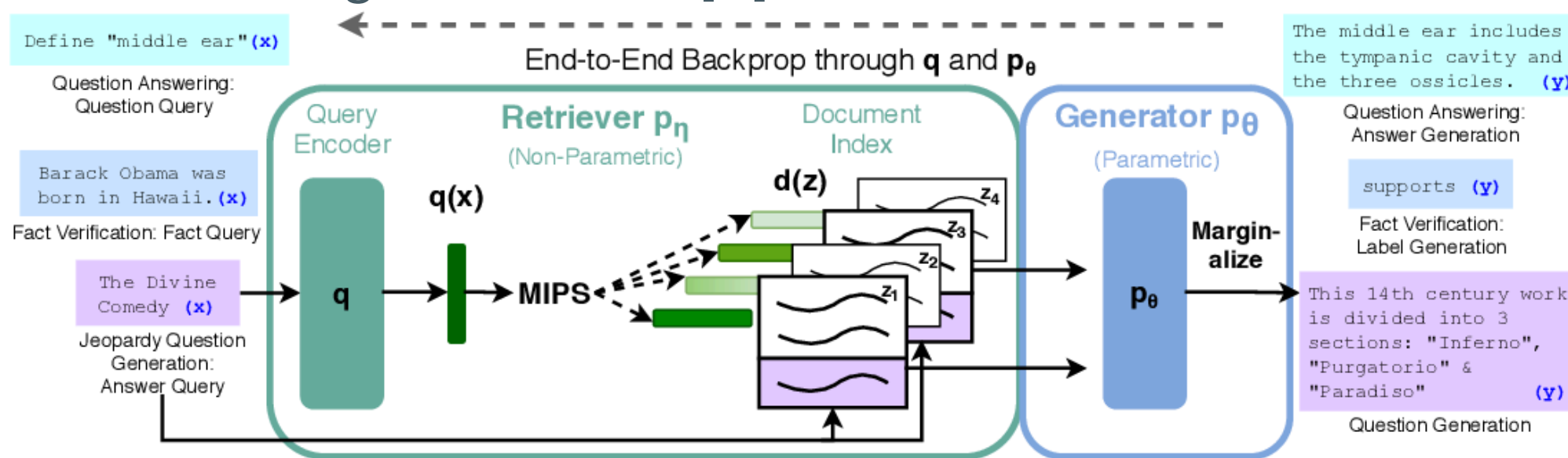
# Layer skip: self speculative decoding

- 10% speed-up
- A single KV cache => low memory overhead
- The main model is still competitive when the last transformer layer is used for prediction despite a different training technique.

# More About Performance?

# Retrieval augmented generation (at inference)

The goal of retrieval augmented generation (RAG) is to give access to updated knowledge to a model [8].



RAG's intricacies will be discussed in another chapter.

# Retrieval augmented generation (at inference)

RAG-sequence model

$$p_{\text{RAG-sequence}}(y|x) \approx \sum_{z \in \text{top-}k} p_{\eta}(z|x) \prod_i^N p_{\theta}(y_i|x, z, y_{1:i-1})$$

RAG-token model

$$p_{\text{RAG-token}}(y|x) \approx \prod_i^N \sum_{z \in \text{top-}k} p_{\eta}(z|x) p_{\theta}(y_i|x, z, y_{1:i-1})$$

# Retrieval augmented generation (at inference)

- Although conditioned on retrieved knowledge, output may be a hallucination.
- Most of RAG's performance depends on the chunking method and the retriever.

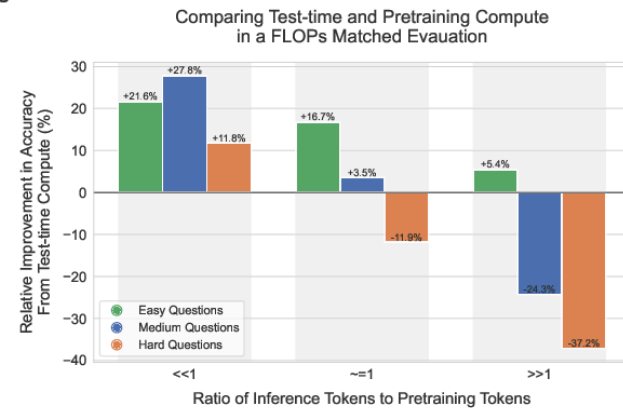
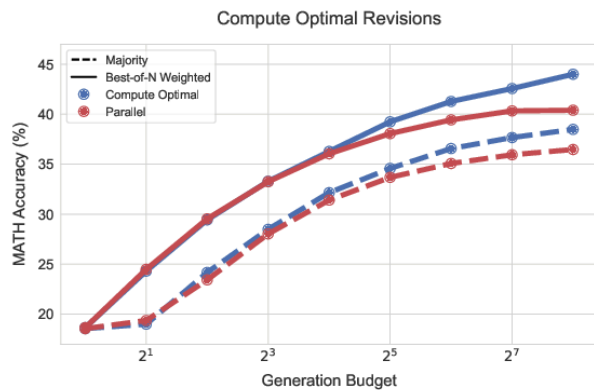
# Test time compute

The goal is to **allocate more compute at inference** to "**natively**" **incorporate chain-of-thought** like decoding.

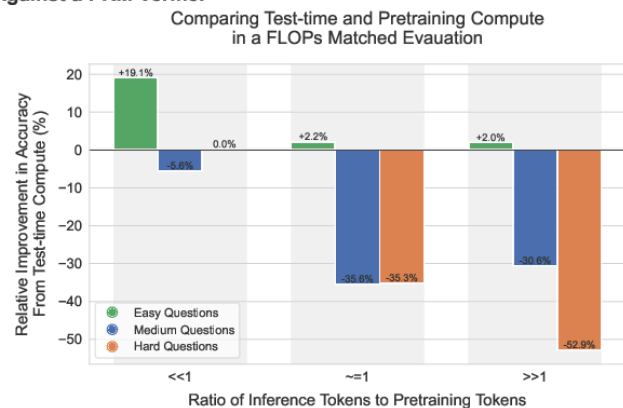
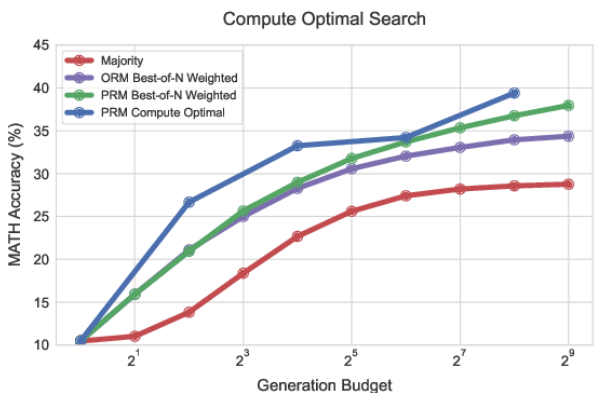
The hypothesis is that **models have good reasoning capabilities** but standard **decoding processes hinder them**.

# Test time compute

## Iteratively Revising Answers at Test-time



## Test-time Search Against a PRM Verifier



[9]

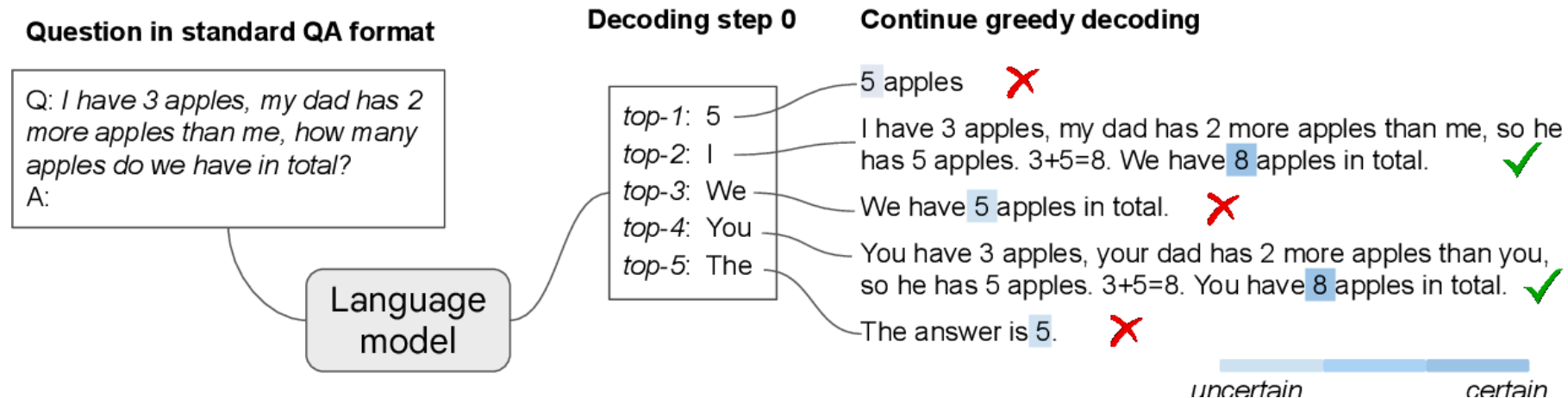
More About Performance?



# Test time compute

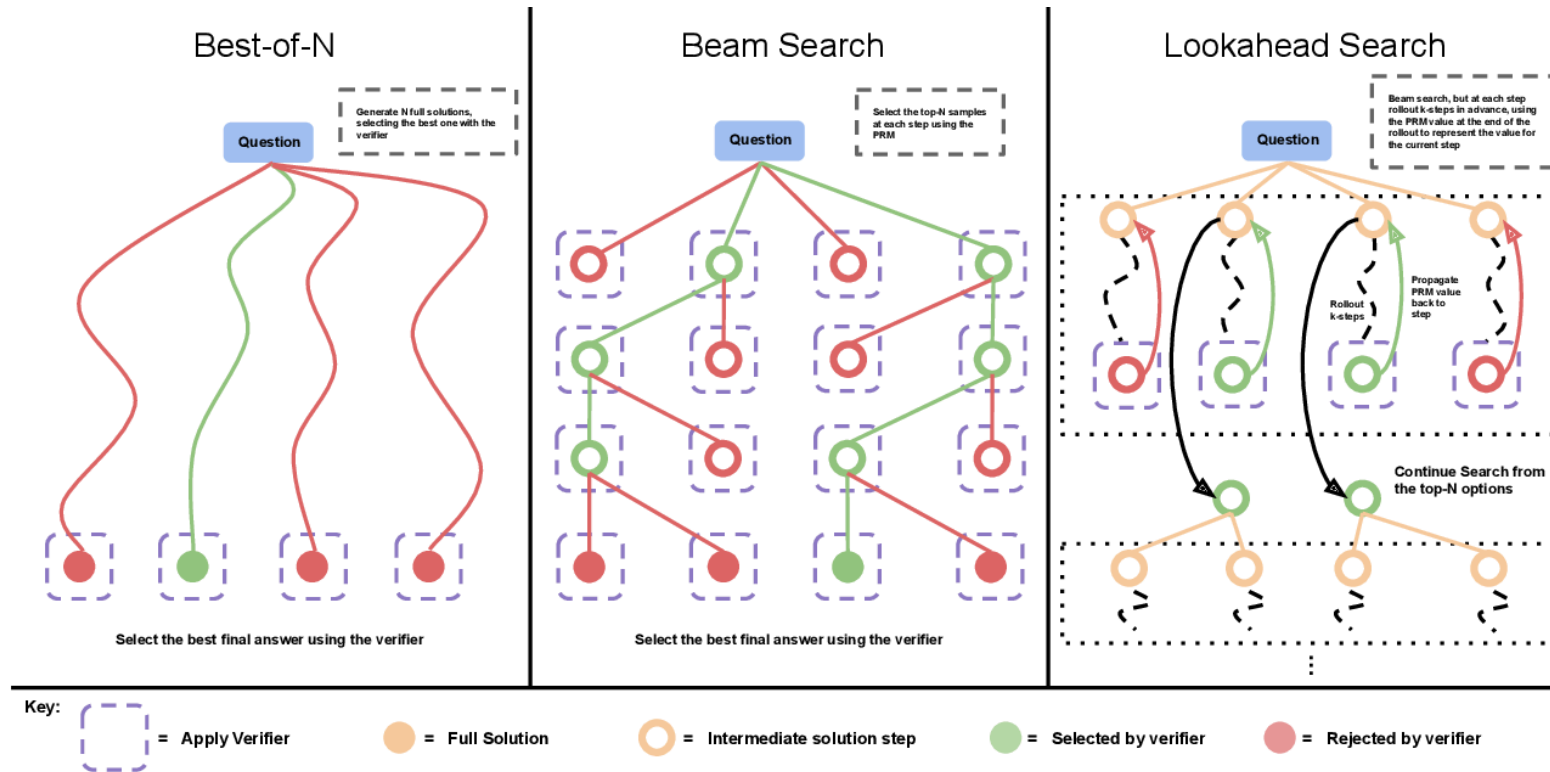
## Search against verifiers [10]:

- Most decoding methods stem from greedy decoding.
- There is no "correct" way of selecting the first token when decoding.



# test time compute

A reward model (verifier) selects the **best answer** based on a **systematic search method**:



# Test time compute

**Modifying proposal distribution:**

**Reinforcement learning-like techniques** where a **model learns to refine its own answer** to reach the optimal one: look at **ReST** [12] and **STaR** [11].

Unlike standard decoding, **the model can backtrack to previous steps.**

# Test time compute

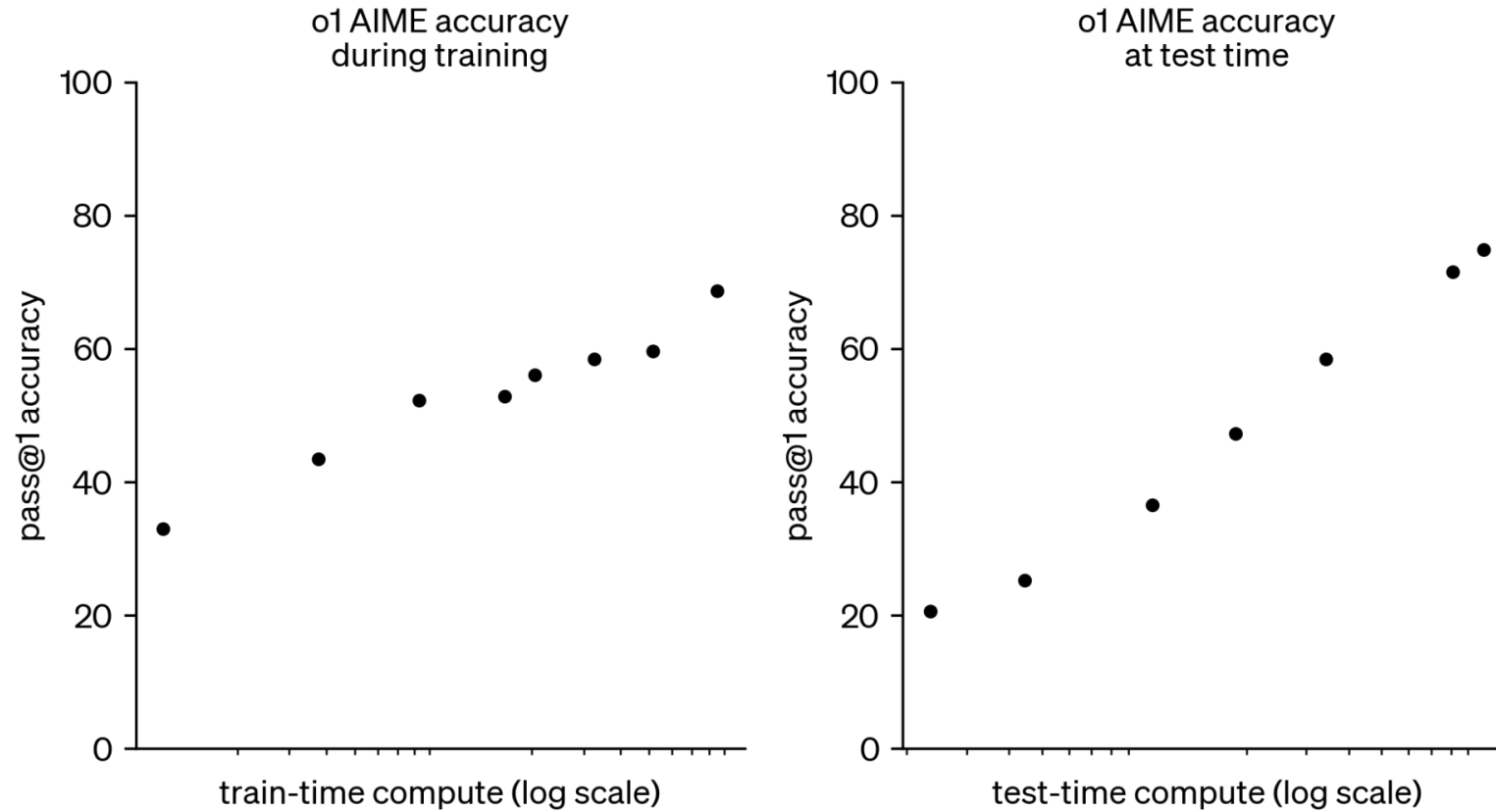
- Borrowing from **ReST**, one could **create candidate responses during inference** and **assess them against a task-specific quality metric** (without updating weights). The highest-quality candidates can then **guide token sampling**.
- **STaR's** multi-path reasoning generation and selection is applicable at test-time by **generating multiple answer paths** and **using consistency checks** or **reranking** to **choose the best response**.

# Test time compute

Takeaways (DeepMind's scaling laws):

- Small models ( $< 10b$ ) are better at answering easy questions when given more TTC than pretraining compute.
- Diminishing return on larger models with more TTC than pretraining compute.

# Test time compute



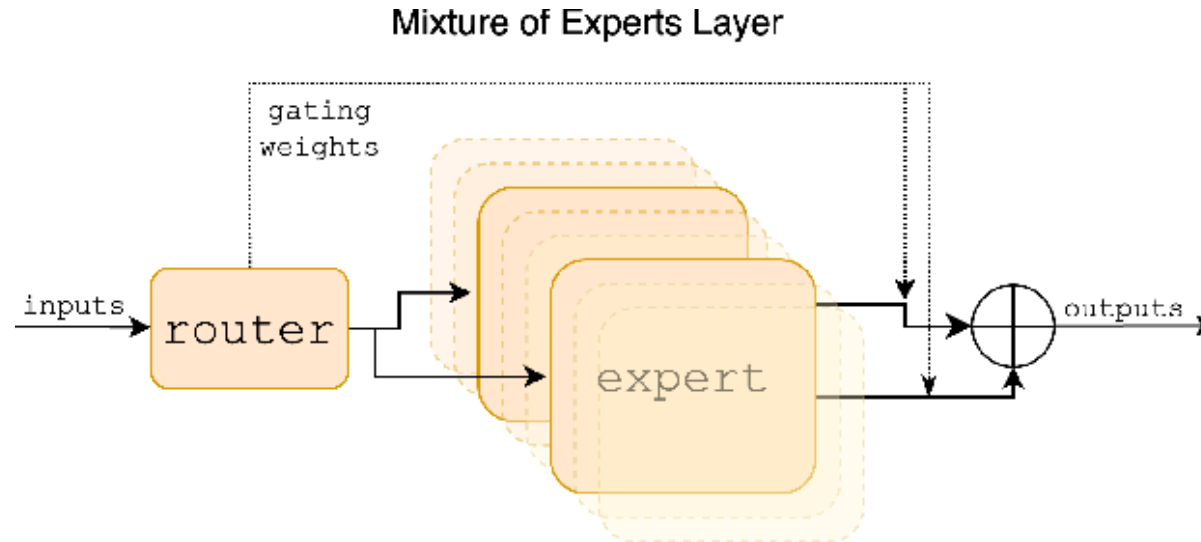
[13]

More About Performance?

# **More About "Balance"?**

# Mixture of experts

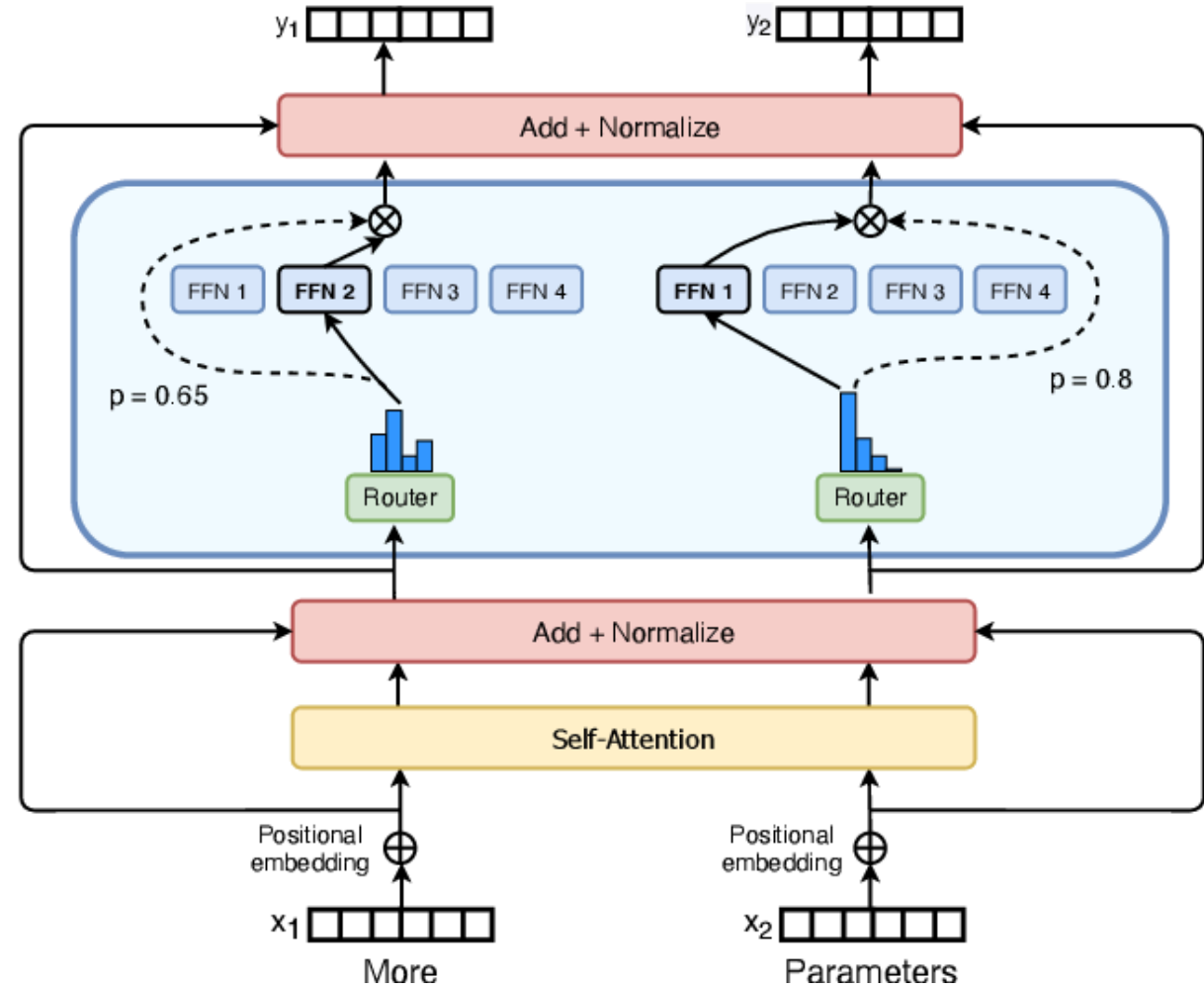
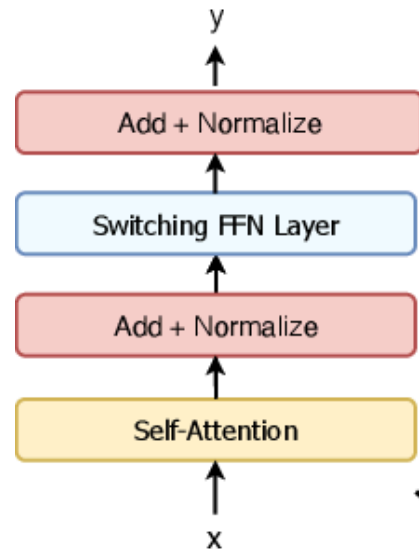
Replacing every FFN in a transformers with a MoE layer [14]?



Divide one FFN network with  $M$  parameters into  $N$  experts with  $M' = \frac{M}{N}$  parameters each.



# Mixture of experts



# Mixture of experts

- Reduced computation during training and inference since we only need to run  $1/N$ th of the FFN weights.
- Unstable during training: can struggle to generalize, thus prone to overfitting.
- Load balancing is crucial: we do not want a subset of experts to be under-utilized.

# Mixture of experts

A learned gating network  $G$  decides which experts  $E$  to send a part of the input:

$$y = \sum_{i=1}^n G(x)_i \times E_i(x)$$

Where  $G(x)_i$  denotes the  $n$ -dimensional output of the gating network for the  $i$ -th expert, and  $E_i(x)$  is the output of the  $i$ -th expert network

# Mixture of experts

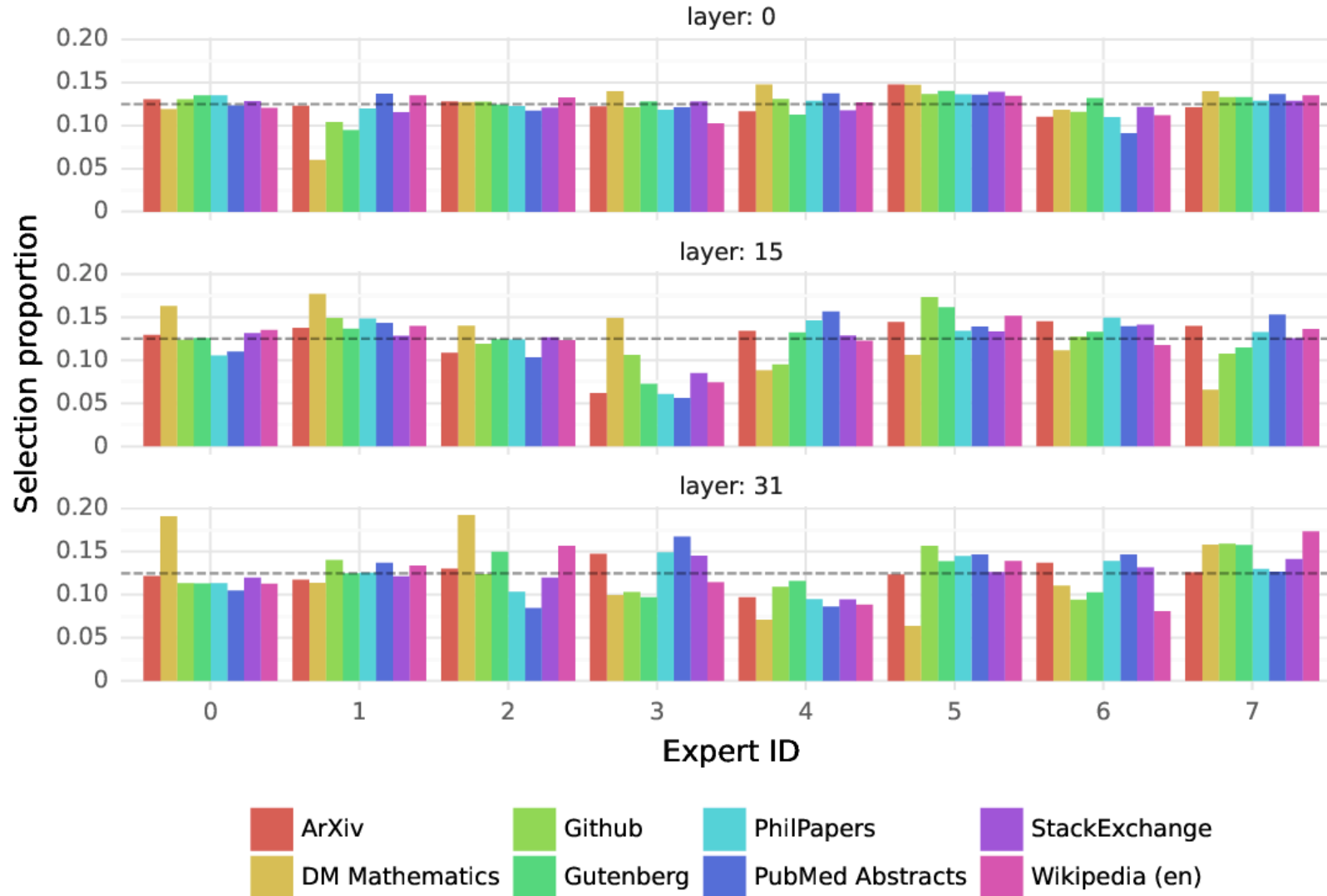
A popular gating function is the softmax function over the top- $k$  logits.

$$G(x) := \text{softmax}(\text{top-}k(x \cdot W_g))$$

In order to have a sparse vector as output

$$\text{top-}k(x \cdot W_g) = \begin{cases} v_i & \text{if } v_i \text{ is in the top } k \text{ of } x \cdot W_g \\ -\infty & \text{otherwise} \end{cases}$$

# Mixture of experts



More About "Balance"?

# Mixture of experts

Layer 0

```
class MoeLayer(nn.Module):
    def __init__(self, experts: List[nn.Module]):
        super().__init__()
        assert len(experts) > 0
        self.experts = nn.ModuleList(experts)
        self.gate = gate
        self.args = moe_args

    def forward(self, inputs: torch.Tensor):
        inputs_squashed = inputs.view(-1, inputs.size(-1))
        gate_logits = self.gate(inputs_squashed)
        weights, selected_experts = torch.topk(
            gate_logits, self.args.num_experts_per_token
        )
        weights = nn.functional.softmax(
            weights,
            dim=-1,
            dtype=torch.float,
        ).type_as(inputs)
        results = torch.zeros_like(inputs_squashed)
        for i, expert in enumerate(self.experts):
            batch_idx, nth_expert = torch.where(
                results[batch_idx] == weights[batch_idx, i]
            )
            inputs_squashed[batch_idx] = expert(inputs_squashed[batch_idx])
        return results.view_as(inputs)
```

Question: Solve  $-42*r + 27*c = -1167$  and  $130*r$   
Answer: 4

Question: Calculate  $-841880142.544 + 411127$ .  
Answer:  $-841469015.544$

Question: Let  $x(g) = 9*g + 1$ . Let  $q(c) = 2*c +$   
Answer:  $54*a - 30$

A model airplane flies slower when flying into the wind and faster with wind at its back. When launched right angles to the wind, a cross wind, its ground speed compared with flying in still air is  
(A) the same (B) greater (C) less (D) either greater or less depending on wind speed

Layer 15

```
class MoeLayer(nn.Module):
    def __init__(self, experts: List[nn.Module]):
        super().__init__()
        assert len(experts) > 0
        self.experts = nn.ModuleList(experts)
        self.gate = gate
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    def forward(self, inputs: torch.Tensor):
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Layer 31

```
class MoeLayer(nn.Module):
    def __init__(self, experts: List[nn.Module]):
        super().__init__()
        assert len(experts) > 0
        self.experts = nn.ModuleList(experts)
        self.gate = gate
        self.args = moe_args

    def forward(self, inputs: torch.Tensor):
        inputs_squashed = inputs.view(-1, inputs.size(-1))
        gate_logits = self.gate(inputs_squashed)
        weights, selected_experts = torch.topk(
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        weights = nn.functional.softmax(
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# Questions?

# References



- [1] Hoffmann, Jordan, et al. "Training compute-optimal large language models." arXiv preprint arXiv:2203.15556 (2022).
- [2] Fu, Qichen, et al. "Lazyllm: Dynamic token pruning for efficient long context llm inference." arXiv preprint arXiv:2407.14057 (2024).
- [3] Jawahar, Ganesh, Benoît Sagot, and Djamé Seddah. "What does BERT learn about the structure of language?." ACL 2019-57th Annual Meeting of the Association for Computational Linguistics. 2019.
- [4] Chung, Hyung Won, et al. "Rethinking embedding coupling in pre-trained language models." arXiv preprint arXiv:2010.12821 (2020).

[5] Leviathan, Yaniv, Matan Kalman, and Yossi Matias. "Fast inference from transformers via speculative decoding." International Conference on Machine Learning. PMLR, 2023.

[6] He, Kaiming, et al. "Deep residual learning for image recognition." Proceedings of the IEEE conference on computer vision and pattern recognition. 2016.

[7] Elhoushi, Mostafa, et al. "Layer skip: Enabling early exit inference and self-speculative decoding." arXiv preprint arXiv:2404.16710 (2024).

[8] Lewis, Patrick, et al. "Retrieval-augmented generation for knowledge-intensive nlp tasks." *Advances in Neural Information Processing Systems* 33 (2020): 9459-9474.

[9] Snell, Charlie, et al. "Scaling llm test-time compute optimally can be more effective than scaling model parameters." *arXiv preprint arXiv:2408.03314* (2024).

[10] Wang, Xuezhi, and Denny Zhou. "Chain-of-thought reasoning without prompting." *arXiv preprint arXiv:2402.10200* (2024).

[11] Zelikman, Eric, et al. "Star: Bootstrapping reasoning with reasoning." Advances in Neural Information Processing Systems 35 (2022): 15476-15488.

[12] Gulcehre, Caglar, et al. "Reinforced self-training (rest) for language modeling." arXiv preprint arXiv:2308.08998 (2023).

[13] [Learning to Reason with LLMs](#) (2024).

[14] Jiang, Albert Q., et al. "Mixtral of experts." arXiv preprint arXiv:2401.04088 (2024).