

Parameter Efficient Fine-Tuning

NLP: Fall 2024

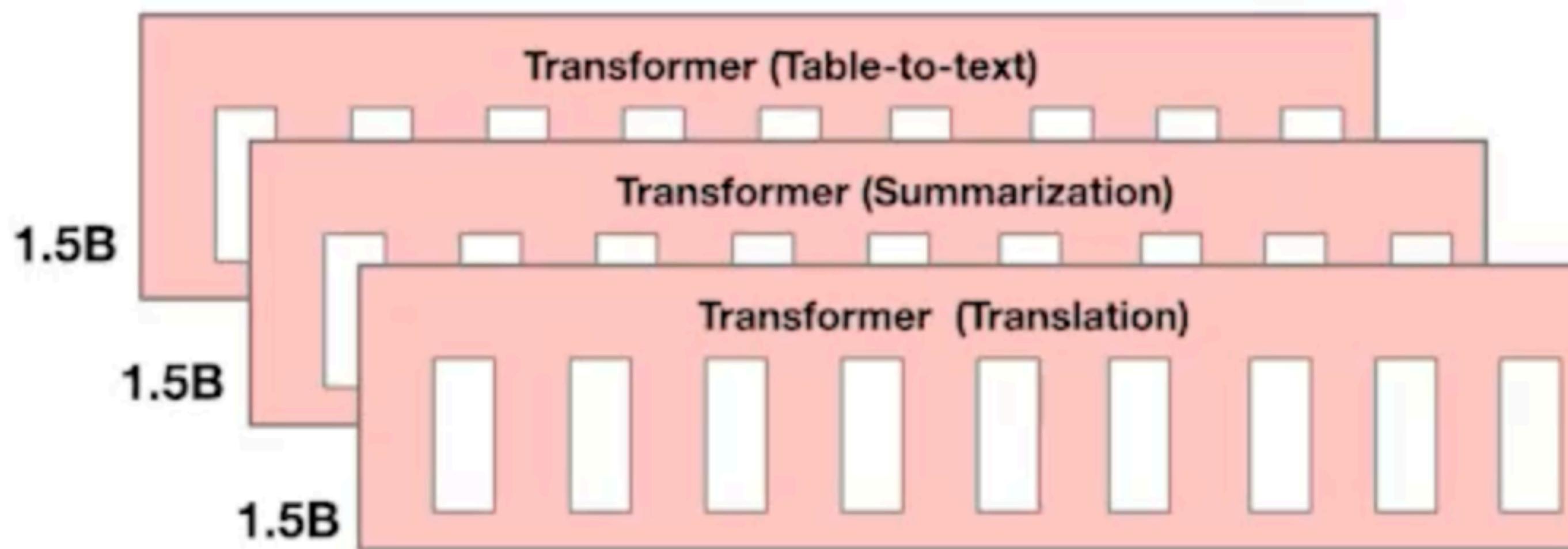
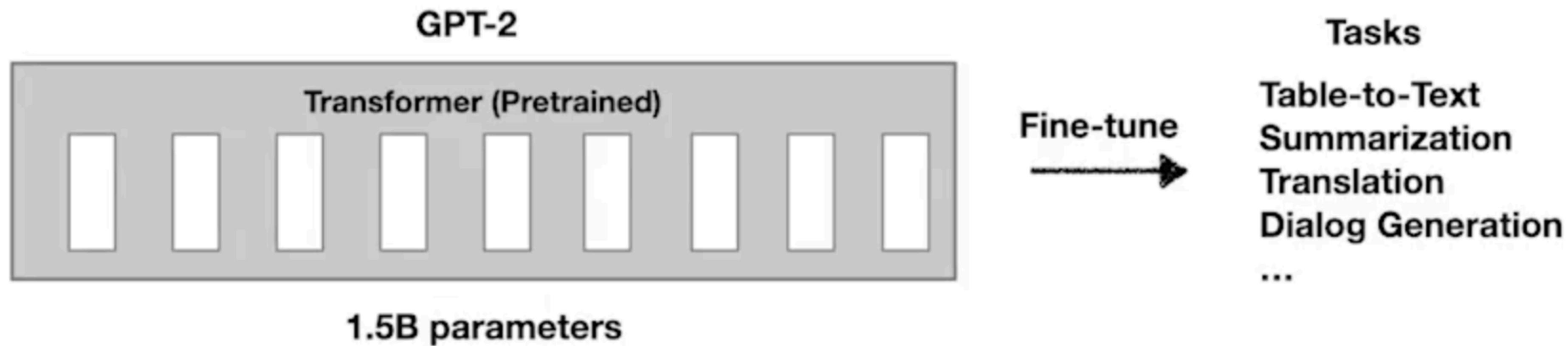
Anoop Sarkar

Prefix Tuning

Li and Liang, ACL 2021

<https://aclanthology.org/2021.acl-long.353>

Why not just use fine-tuning



Each task requires a full
model copy

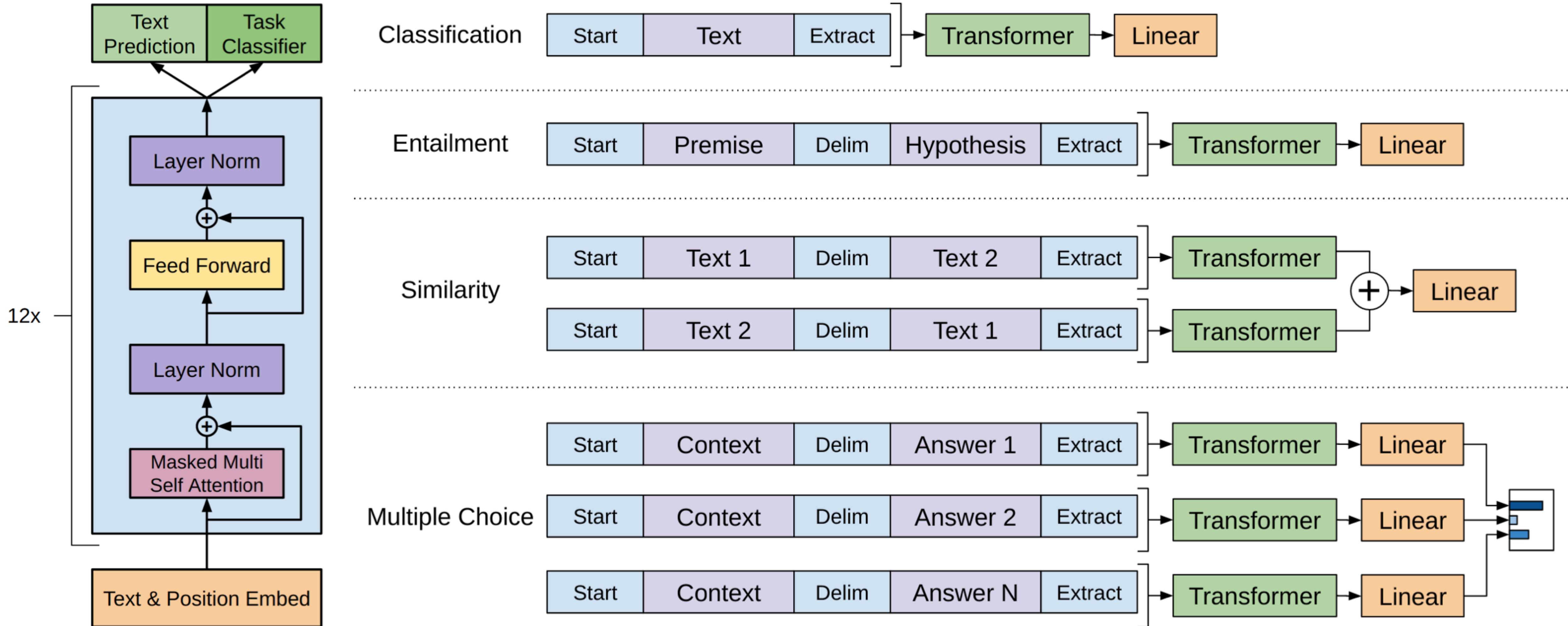
In-context learning using prompts



- No task specific fine-tuning
- Preserves the LM

- Cannot use large training set
- Manual prompts can be suboptimal
- Cannot be used with smaller LMs like GPT-2

In-context learning using prompts



In-context learning using prompts

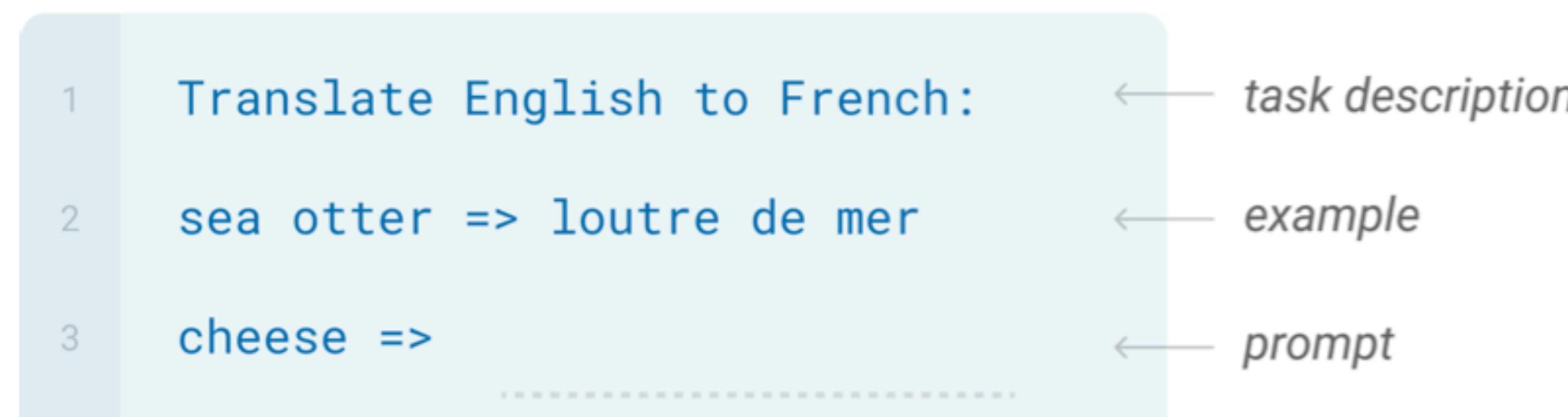
Zero-shot

The model predicts the answer given only a natural language description of the task. No gradient updates are performed.



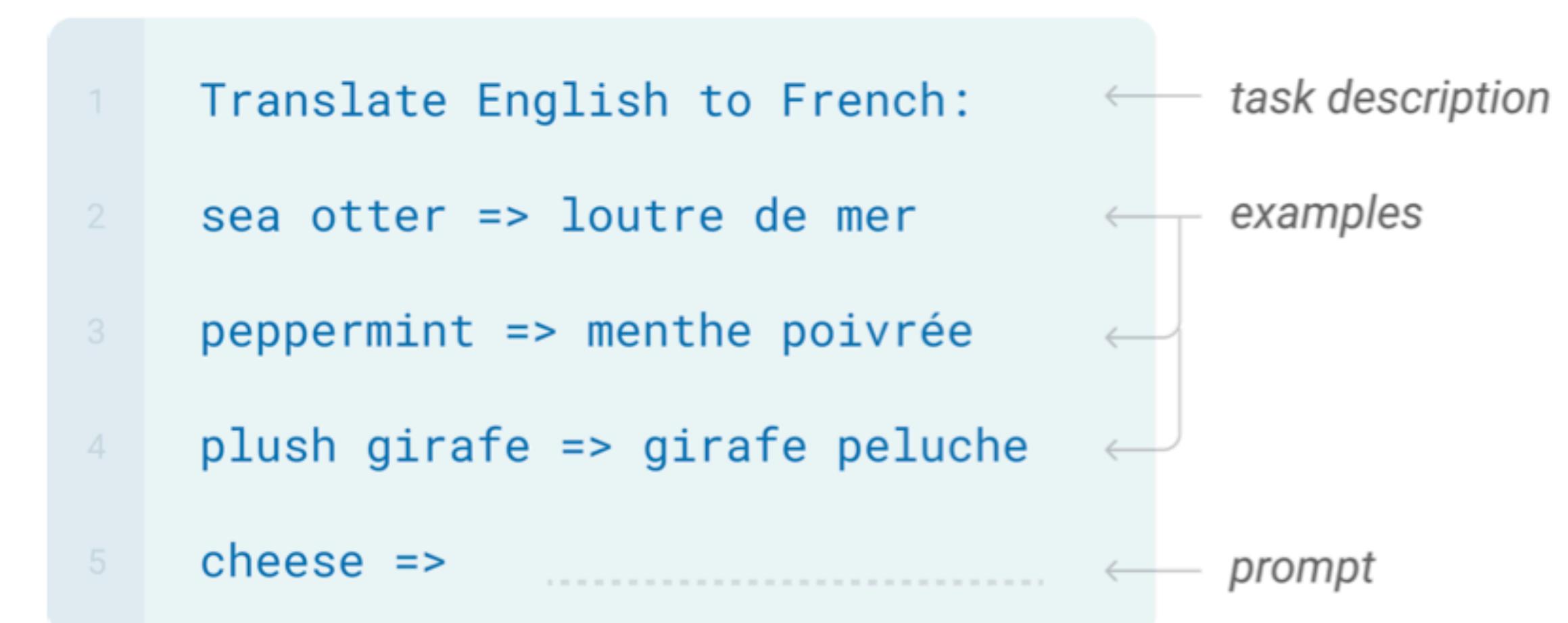
One-shot

In addition to the task description, the model sees a single example of the task. No gradient updates are performed.

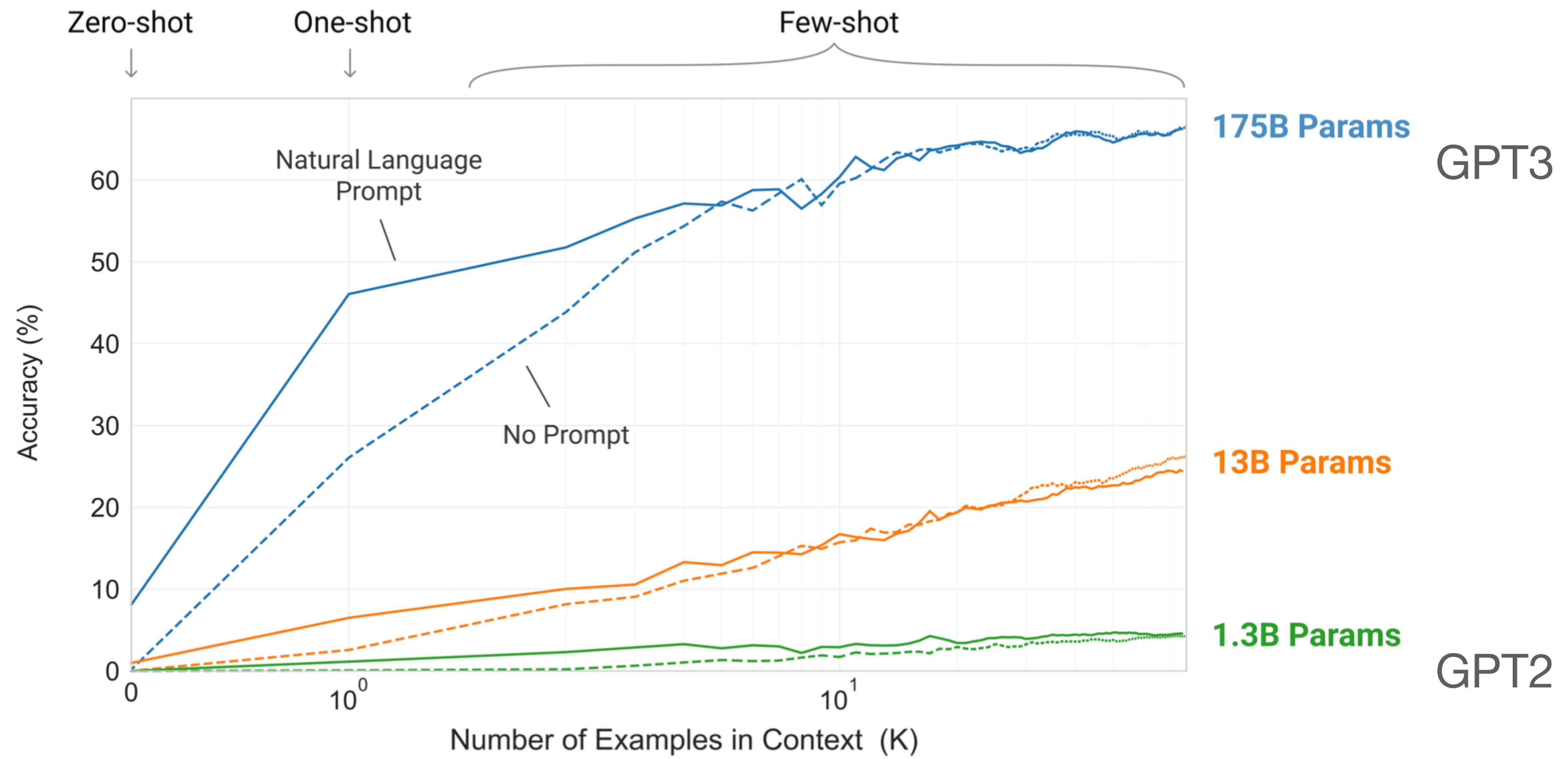


Few-shot

In addition to the task description, the model sees a few examples of the task. No gradient updates are performed.



In-context learning using prompts



Prompt tuning: enabling smaller LMs

iPet: better prompts for each task improves accuracy for small LMs

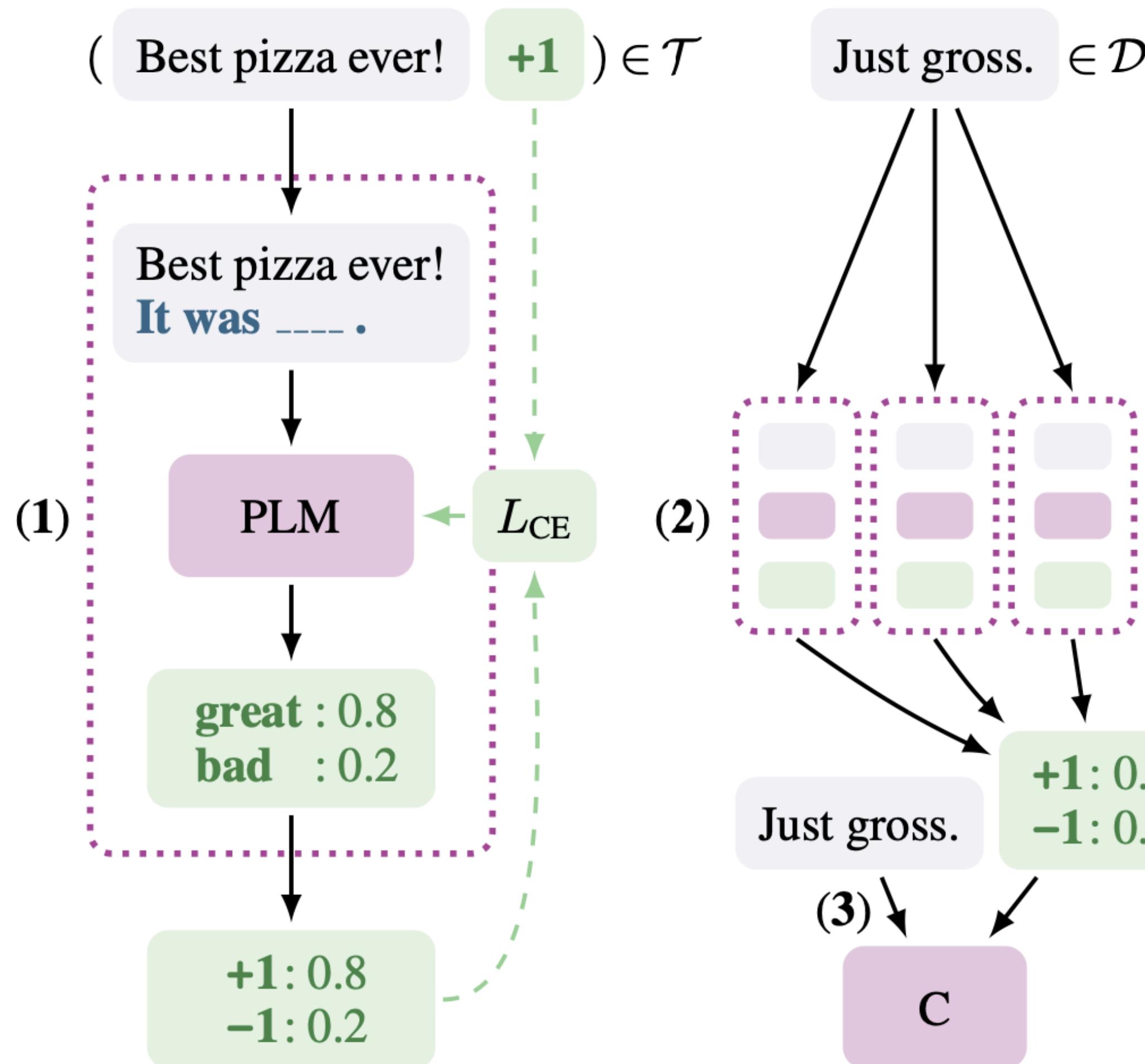


Figure 1: PET for sentiment classification. (1) A number of patterns encoding some form of task description are created to convert training examples to cloze questions; for each pattern, a pretrained language model is finetuned. (2) The ensemble of trained models annotates unlabeled data. (3) A classifier is trained on the resulting soft-labeled dataset.

Prompt tuning: enabling smaller LMs

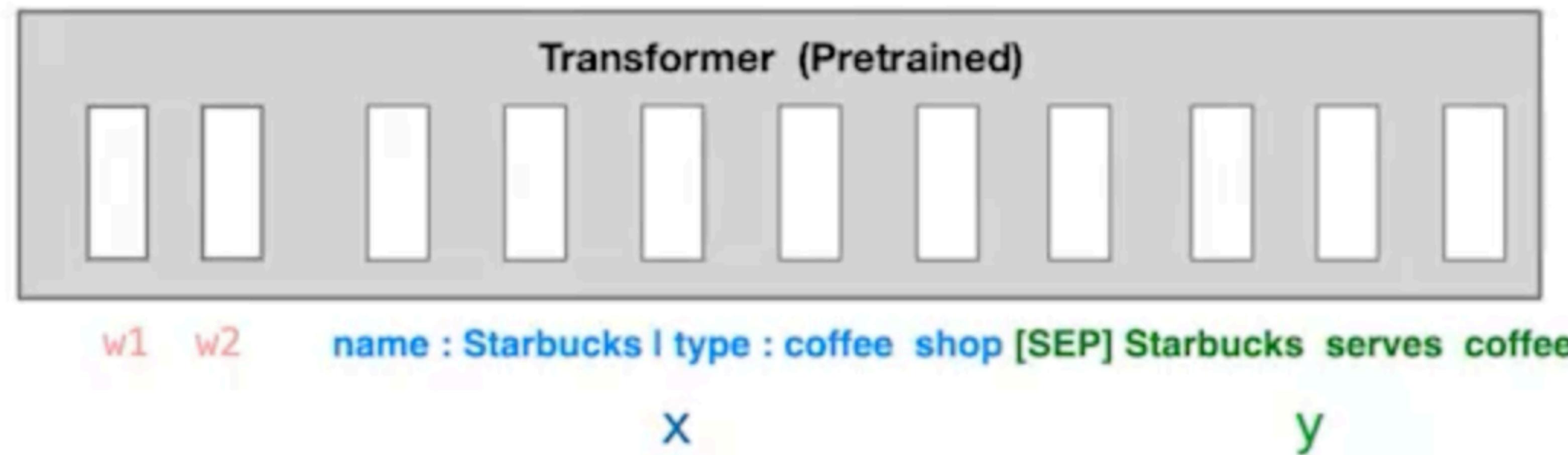
Line	Examples	Method	Yelp	AG's	Yahoo	MNLI (m/mm)
1	$ \mathcal{T} = 0$	unsupervised (avg)	33.8 ± 9.6	69.5 ± 7.2	44.0 ± 9.1	$39.1 \pm 4.3 / 39.8 \pm 5.1$
2		unsupervised (max)	40.8 ± 0.0	79.4 ± 0.0	56.4 ± 0.0	$43.8 \pm 0.0 / 45.0 \pm 0.0$
3		iPET	56.7 ± 0.2	87.5 ± 0.1	70.7 ± 0.1	$53.6 \pm 0.1 / 54.2 \pm 0.1$
4	$ \mathcal{T} = 10$	supervised	21.1 ± 1.6	25.0 ± 0.1	10.1 ± 0.1	$34.2 \pm 2.1 / 34.1 \pm 2.0$
5		PET	52.9 ± 0.1	87.5 ± 0.0	63.8 ± 0.2	$41.8 \pm 0.1 / 41.5 \pm 0.2$
6		iPET	57.6 ± 0.0	89.3 ± 0.1	70.7 ± 0.1	$43.2 \pm 0.0 / 45.7 \pm 0.1$
7	$ \mathcal{T} = 50$	supervised	44.8 ± 2.7	82.1 ± 2.5	52.5 ± 3.1	$45.6 \pm 1.8 / 47.6 \pm 2.4$
8		PET	60.0 ± 0.1	86.3 ± 0.0	66.2 ± 0.1	$63.9 \pm 0.0 / 64.2 \pm 0.0$
9		iPET	60.7 ± 0.1	88.4 ± 0.1	69.7 ± 0.0	$67.4 \pm 0.3 / 68.3 \pm 0.3$
10	$ \mathcal{T} = 100$	supervised	53.0 ± 3.1	86.0 ± 0.7	62.9 ± 0.9	$47.9 \pm 2.8 / 51.2 \pm 2.6$
11		PET	61.9 ± 0.0	88.3 ± 0.1	69.2 ± 0.0	$74.7 \pm 0.3 / 75.9 \pm 0.4$
12		iPET	62.9 ± 0.0	89.6 ± 0.1	71.2 ± 0.1	$78.4 \pm 0.7 / 78.6 \pm 0.5$
13	$ \mathcal{T} = 1000$	supervised	63.0 ± 0.5	86.9 ± 0.4	70.5 ± 0.3	$73.1 \pm 0.2 / 74.8 \pm 0.3$
14		PET	64.8 ± 0.1	86.9 ± 0.2	72.7 ± 0.0	$85.3 \pm 0.2 / 85.5 \pm 0.4$

Table 1: Average accuracy and standard deviation for RoBERTa (large) on Yelp, AG's News, Yahoo and MNLI (m:matched/mm:mismatched) for five training set sizes $|\mathcal{T}|$.

Prefix Tuning

Intuition

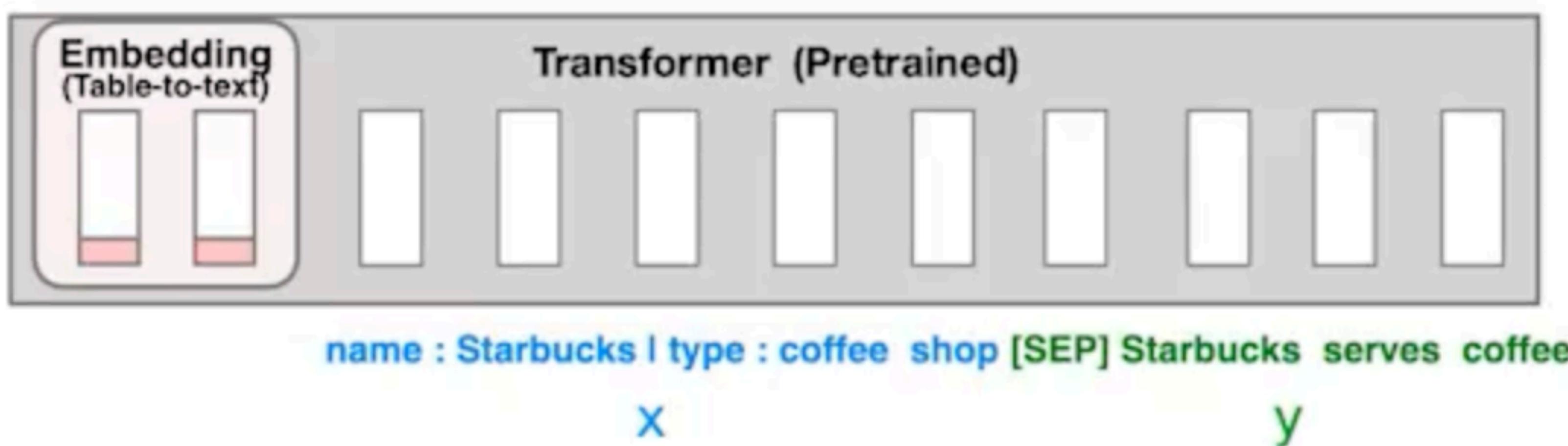
- Learn a good instruction that can steer the LM to produce the right output
- Optimize finding actual words
- Involves discrete optimization which is challenging and not expressive



Prefix Tuning

Intuition

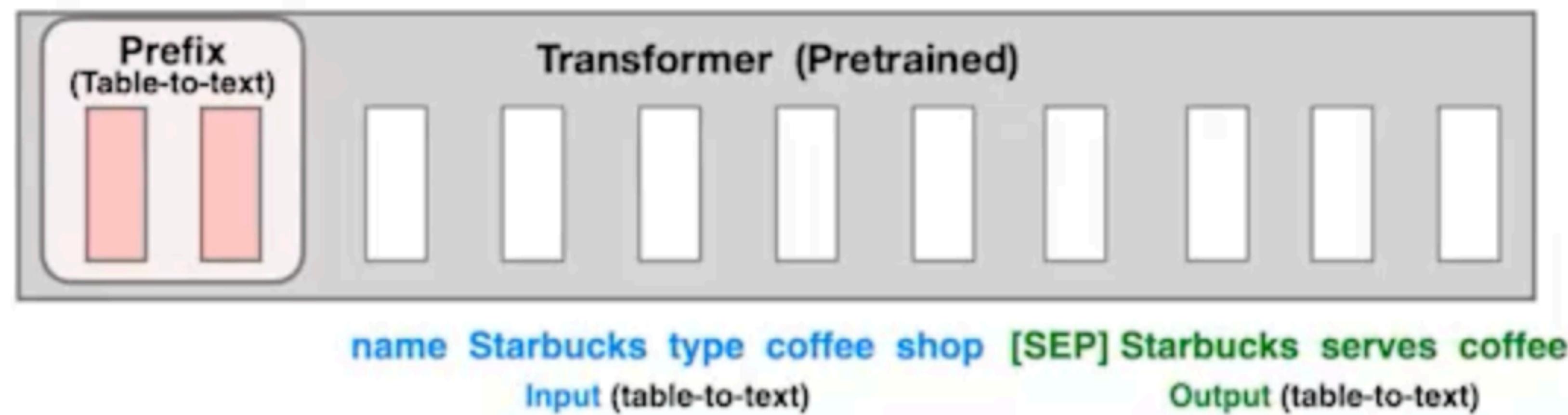
- Optimize the instruction as continuous word embeddings
- More expressive
- Limits the scope of the prompt to a input embeddings



Prefix Tuning

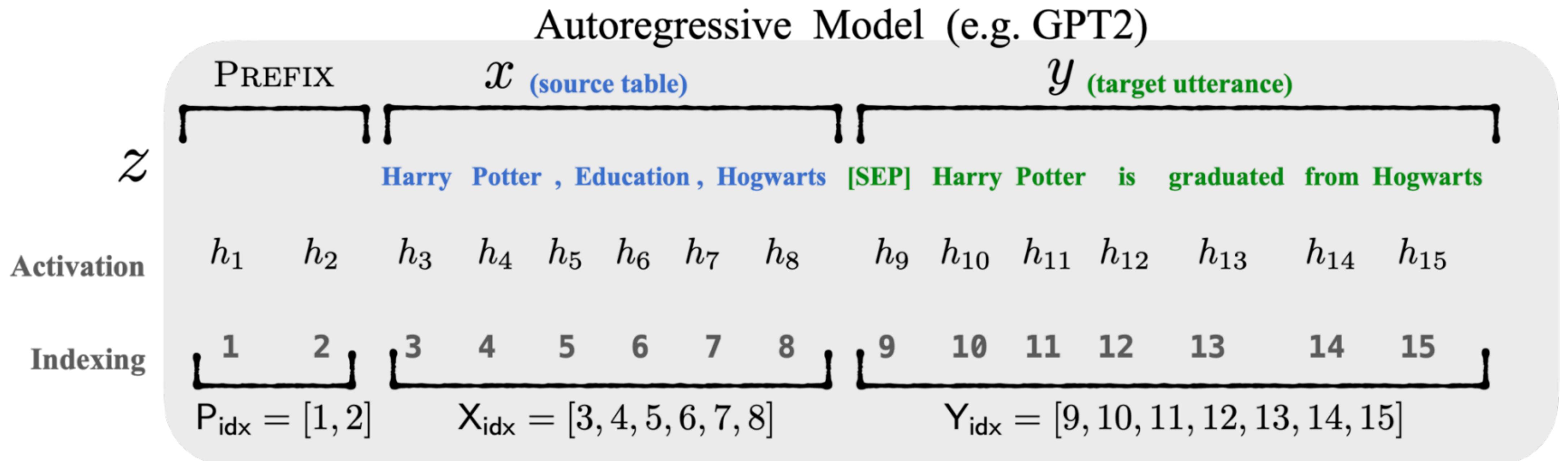
Intuition

- Optimize the instruction as prefix activation for all layers in the instruction
- Very expressive
- All the layers of the prefix can be tuned to create the most expressive prompt



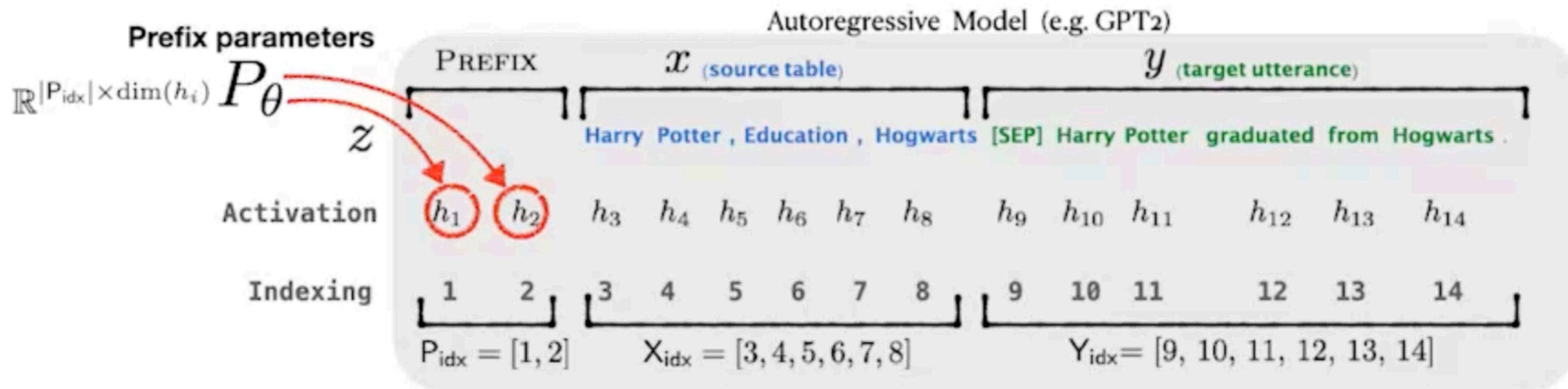
Prefix Tuning

Autoregressive Modelling



Prefix Tuning

$$h_i = \begin{cases} P_\theta[i, :], & \text{if } i \in P_{\text{idx}}, \\ \text{LM}_\phi(z_i, h_{<i}), & \text{otherwise.} \end{cases}$$

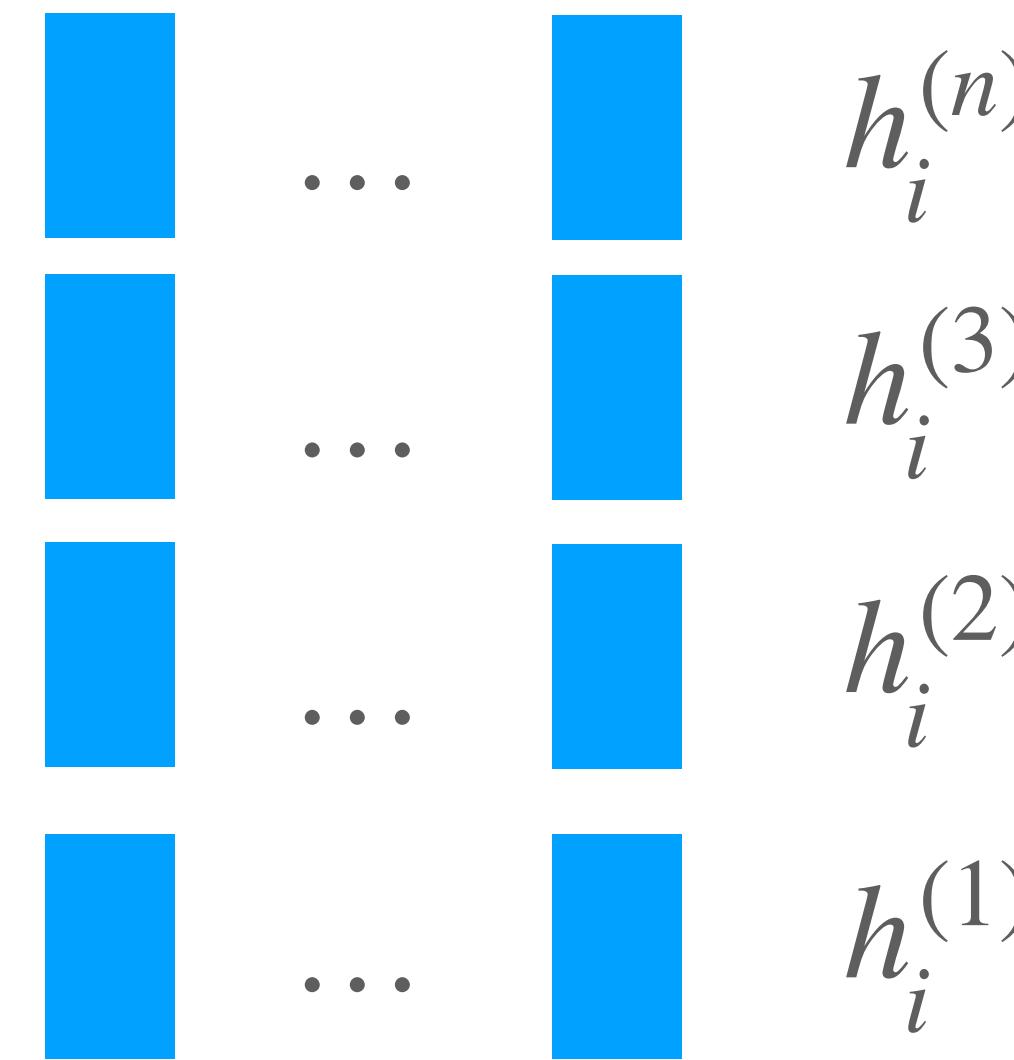


$$\max_{\theta} \log p_{\phi, \theta}(y \mid x) = \sum_{i \in Y_{\text{idx}}} \log p_{\phi, \theta}(z_i \mid h_{<i})$$

freeze LM parameters ϕ
update prefix parameters θ

Prefix Re-parametrization

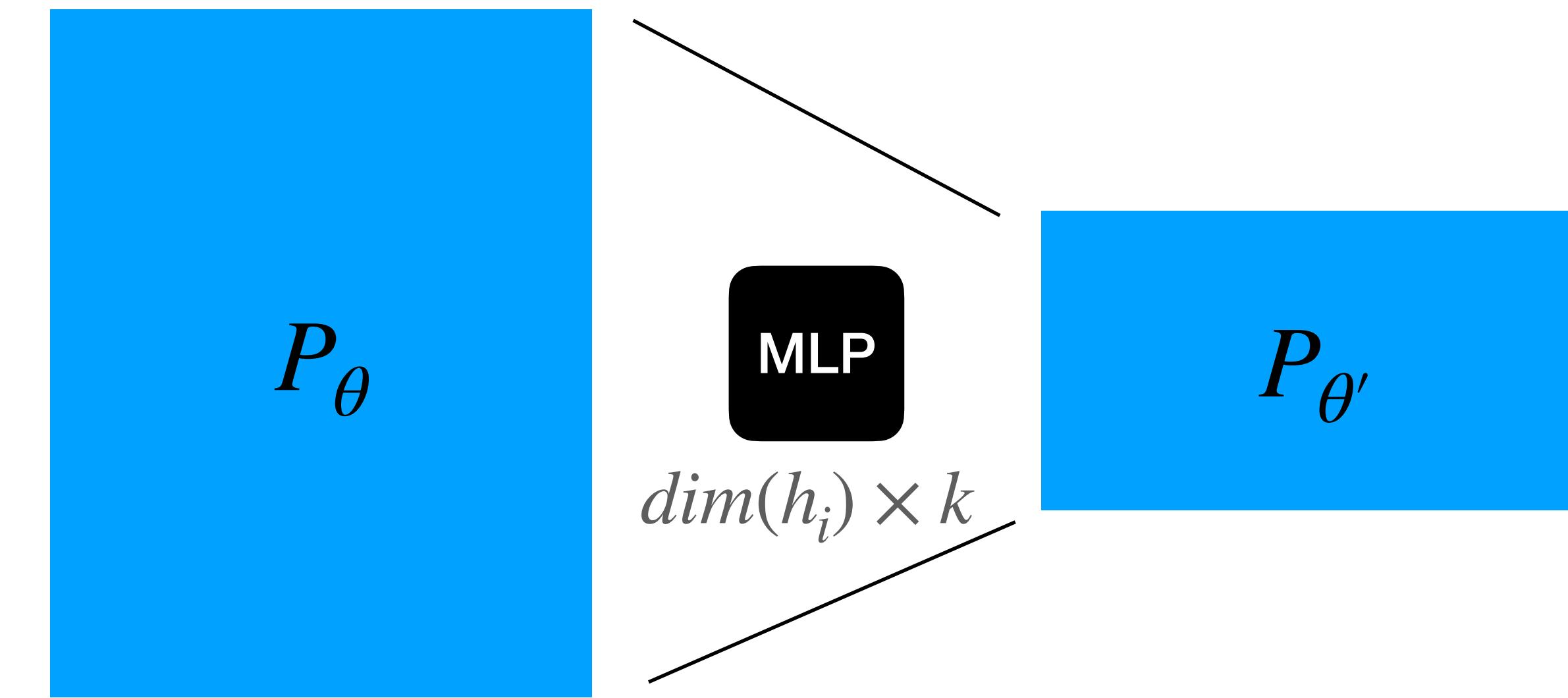
$$h_i = \begin{cases} P_\theta[i, :], & \text{if } i \in P_{idx}, \\ \text{LM}_\phi(z_i, h_{<i}), & \text{otherwise.} \end{cases}$$



$h_1 \dots h_{|P_{idx}|}$

$P_\theta[i, :]$

$|P_{idx}| \times \dim(h_i)$



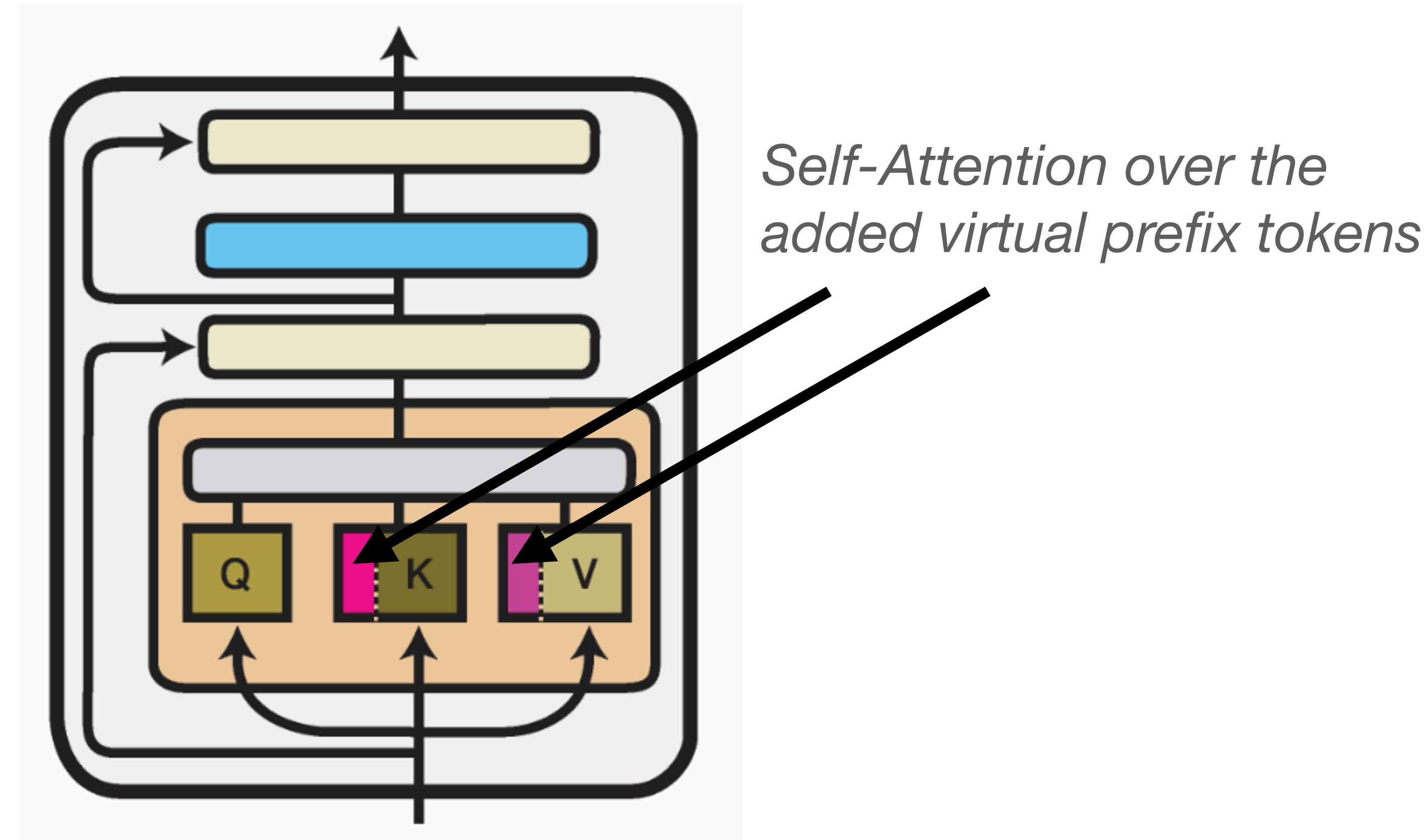
$|P_{idx}| \times \dim(h_i)$

$|P_{idx}| \times k$

Once training is complete
we store only P_θ (throw
away the MLP)

k is 512 for table-to-text
and 800 for summarization

Effect of Prefix Tuning



Prefix Tuning Vs. Finetuning

Source	name : The Eagle type : coffee shop food : Chinese price : cheap customer rating : average area : riverside family friendly : no near : Burger King
Prefix (50)	The Eagle is a cheap Chinese coffee shop located near Burger King.
Prefix (100)	The Eagle is a cheap coffee shop located in the riverside near Burger King. It has average customer ratings.
Prefix (200)	The Eagle is a cheap Chinese coffee shop located in the riverside area near Burger King. It has average customer ratings.
Prefix (500)	The Eagle is a coffee shop that serves Chinese food. It is located in the riverside area near Burger King. It has an average customer rating and is not family friendly.
FT (50)	The Eagle coffee shop is located in the riverside area near Burger King.
FT (100)	The Eagle is a cheap coffee shop near Burger King in the riverside area. It has a low customer rating and is not family friendly.
FT (200)	The Eagle is a cheap Chinese coffee shop with a low customer rating. It is located near Burger King in the riverside area.
FT (500)	The Eagle is a cheap Chinese coffee shop with average customer ratings. It is located in the riverside area near Burger King.

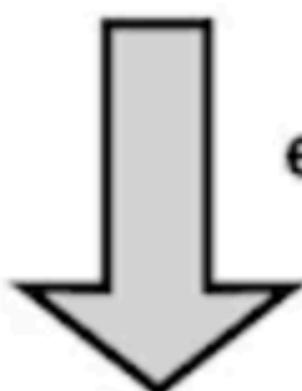
* The number in the parenthesis refers to the training size.

Prefix Tuning

Extrapolation to unseen categories

Trained on 9 categories

Astronaut, University, Monument, Building,
ComicsCharacter, Food, Airport,
SportsTeam, City, and WrittenWork



extrapolates

Test on 5 unseen categories

Athlete, Artist, MeanOfTransportation,
CelestialBody, Politician

x: [103_Colmore_Row | architect | John_Madin]
[John_Madin | birthPlace | Birmingham]
[Birmingham | leaderName | Andrew_Mitchell]

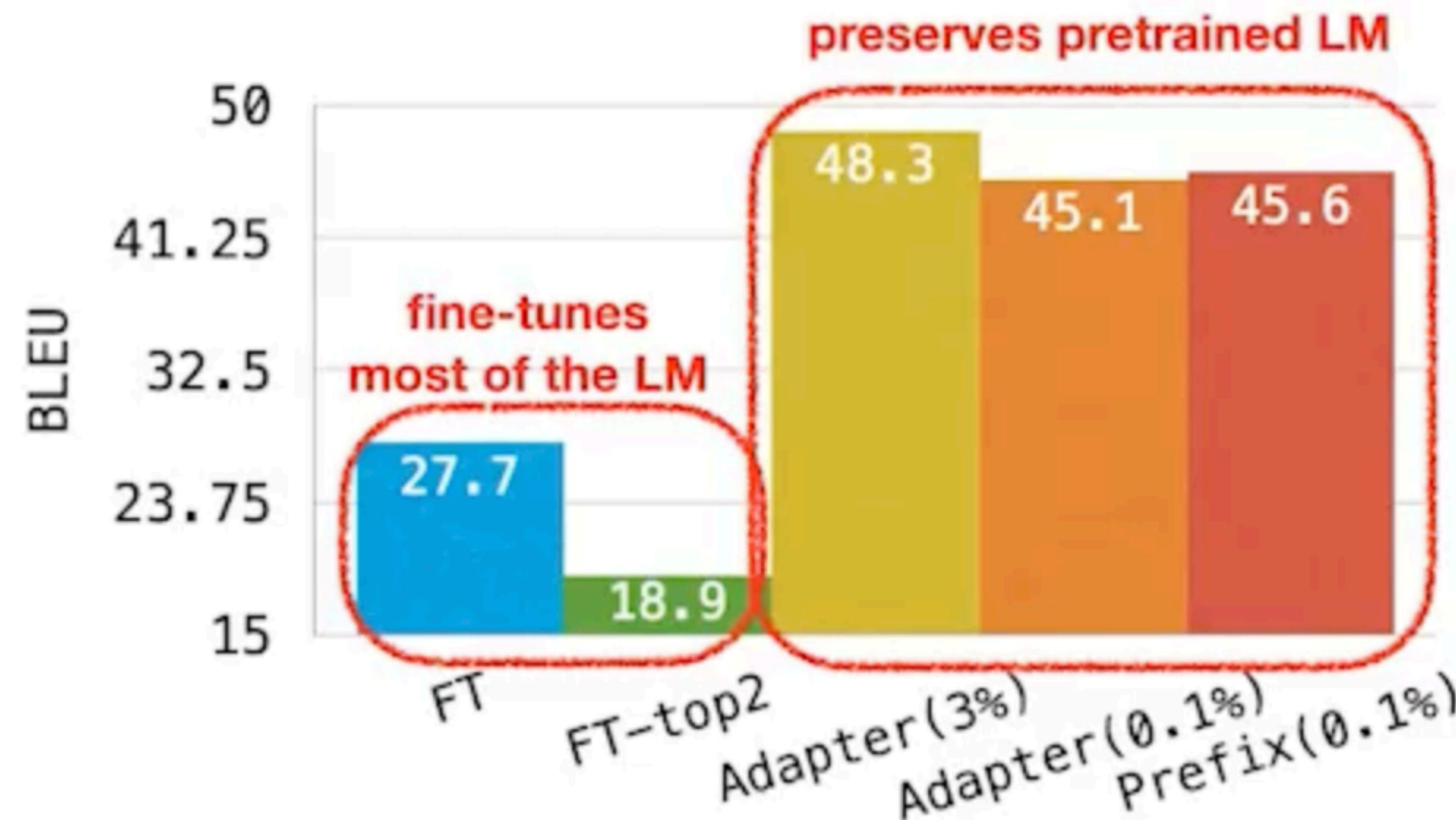
y: John Madin was born in Birmingham (with
Andrew Mitchell as a key leader) and became
an architect, designing 103 Colmore Row.

x: [Albennie_Jones | genre | Rhythm_and_blues]
[Albennie_Jones | birthPlace | Errata,_Mississippi]
[Rhythm_and_blues | derivative | Disco]

y: Albennie Jones, born in Errata, Mississippi, is
a performer of rhythm and blues, of which
disco is a derivative.

Prefix Tuning

Extrapolation to unseen categories



aka PaSTA

Parameter-Efficient Tuning with Special Token Adaptation

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<https://aclanthology.org/2023.eacl-main.60.pdf>

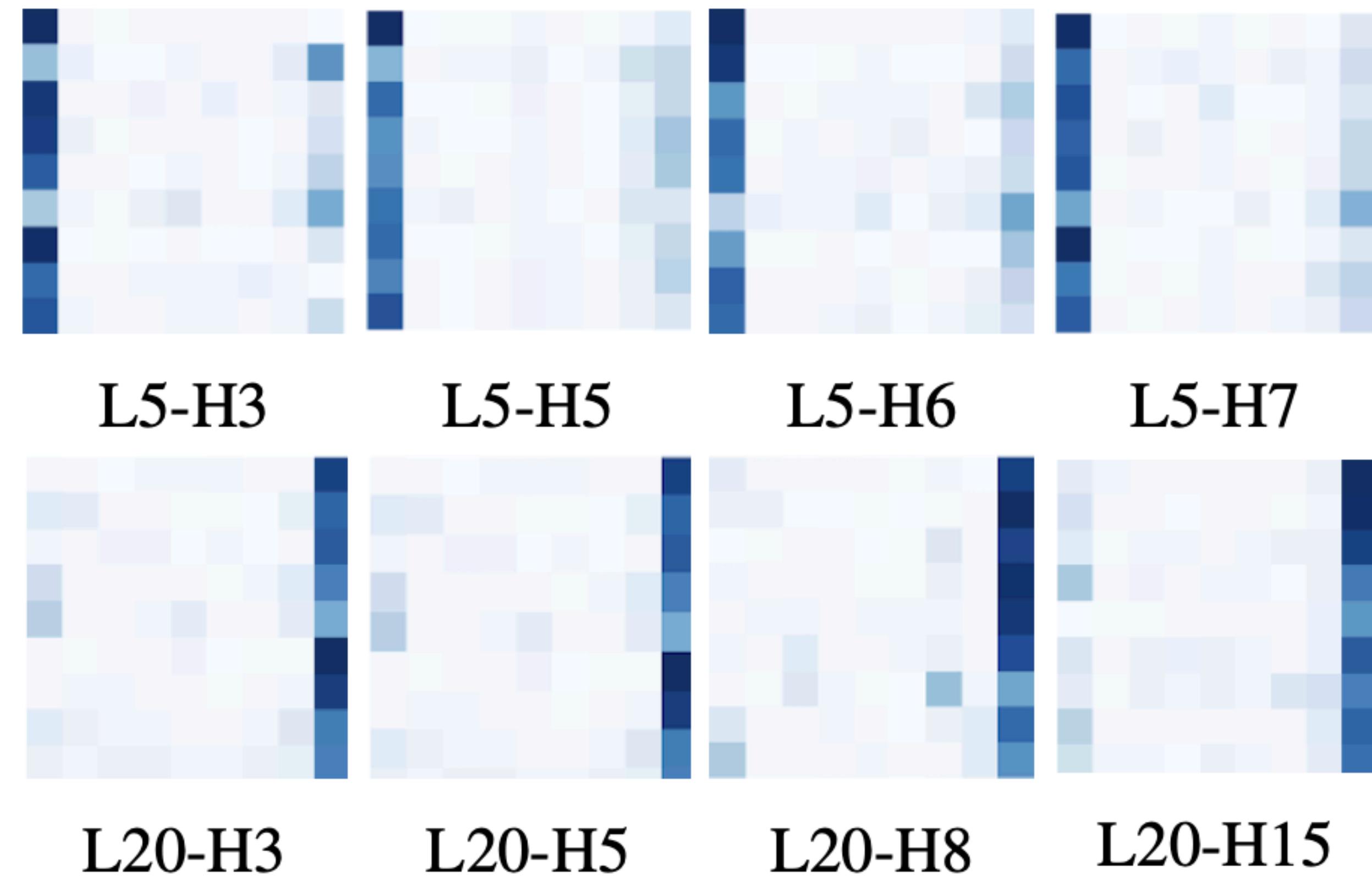


Figure 1: Examples of vertical attention heads in the 5-th and 20-th layer of BERT-large with a random sample from CoLA (Warstadt et al., 2019) as input. Heads in the first row and second row assign most of maximal attention weights to [CLS] and [SEP] respectively.

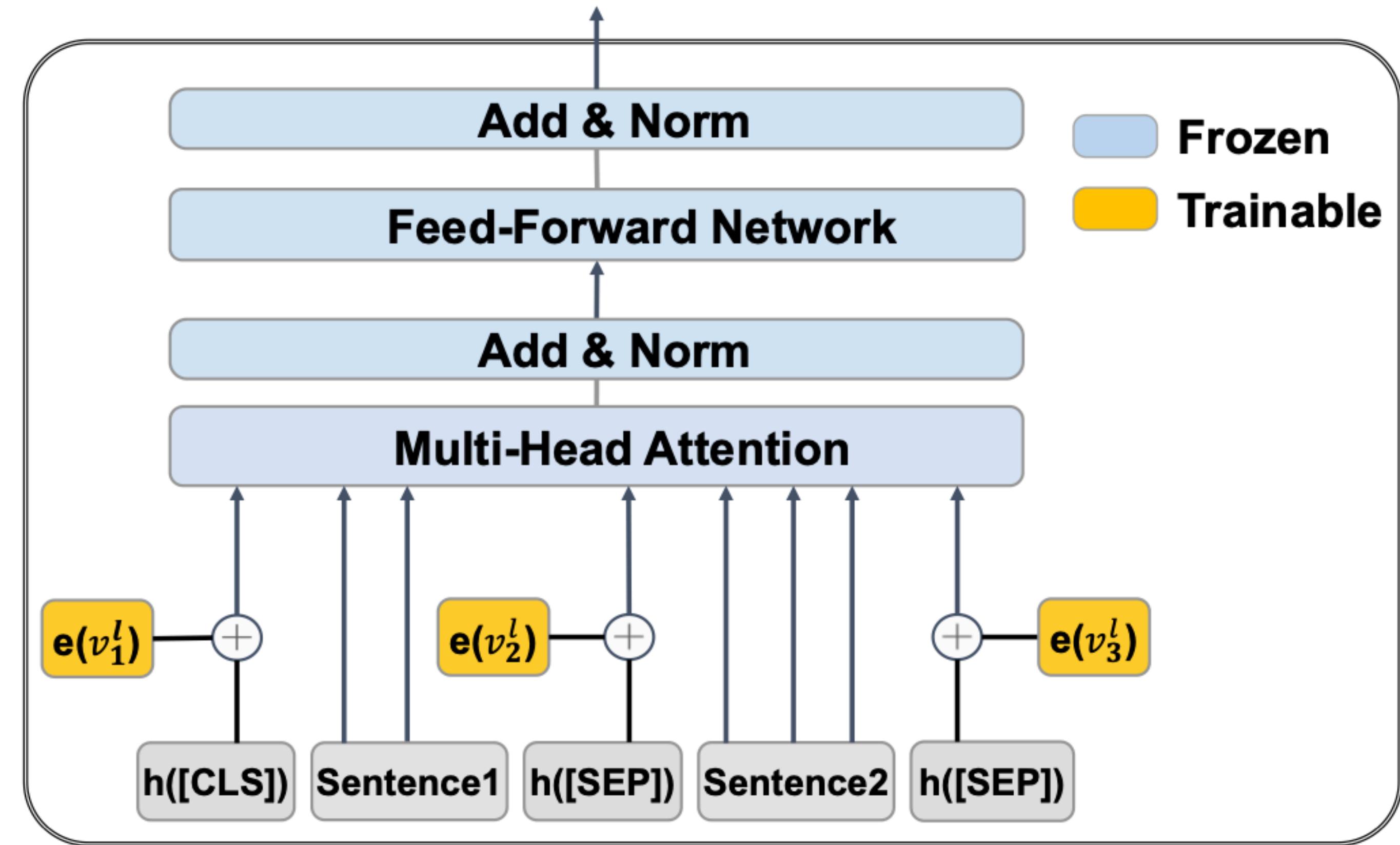


Figure 2: Architecture of PASTA layer in Transformer. Skip-connections in Transformers are not shown for brevity. At layer l we add a trainable vector $\mathbf{e}(\mathbf{v}_p^l) \in \mathbb{R}^d$ to the hidden representation of the p -th special token in the input sequence, and freeze the weights of the PLM.

Results on GLUE with BERT-large

	%Param	RTE	CoLA	STS-B	MRPC	SST-2	QNLI	MNLI(m/mm)	QQP	Avg.
		acc.	mcc.	Spearman	F1	acc.	acc.	acc.	F1	
Full Finetuning*	100%	70.1	60.5	86.5	89.3	94.9	92.7	86.7/85.9	72.1	81.6
Adapter**	3.6%	71.5	59.5	86.9	89.5	94.0	90.7	84.9/85.1	71.8	81.1
Diff-Prune†	0.5%	70.6	61.1	86.0	89.7	94.1	93.3	86.4/86.0	71.1	81.5
P-tuning v2	0.29%	70.1	60.1	86.8	88.0	94.6	92.3	85.3/84.9	70.6	81.0
BitFit‡	0.08%	72.0	59.7	85.5	88.9	94.2	92.0	84.5/84.8	70.5	80.9
PASTA	0.015%-0.022%	70.8	62.3	86.6	87.9	94.4	92.8	83.4/83.4	68.6	80.9

Ablation study on GLUE and CoNLL-2003

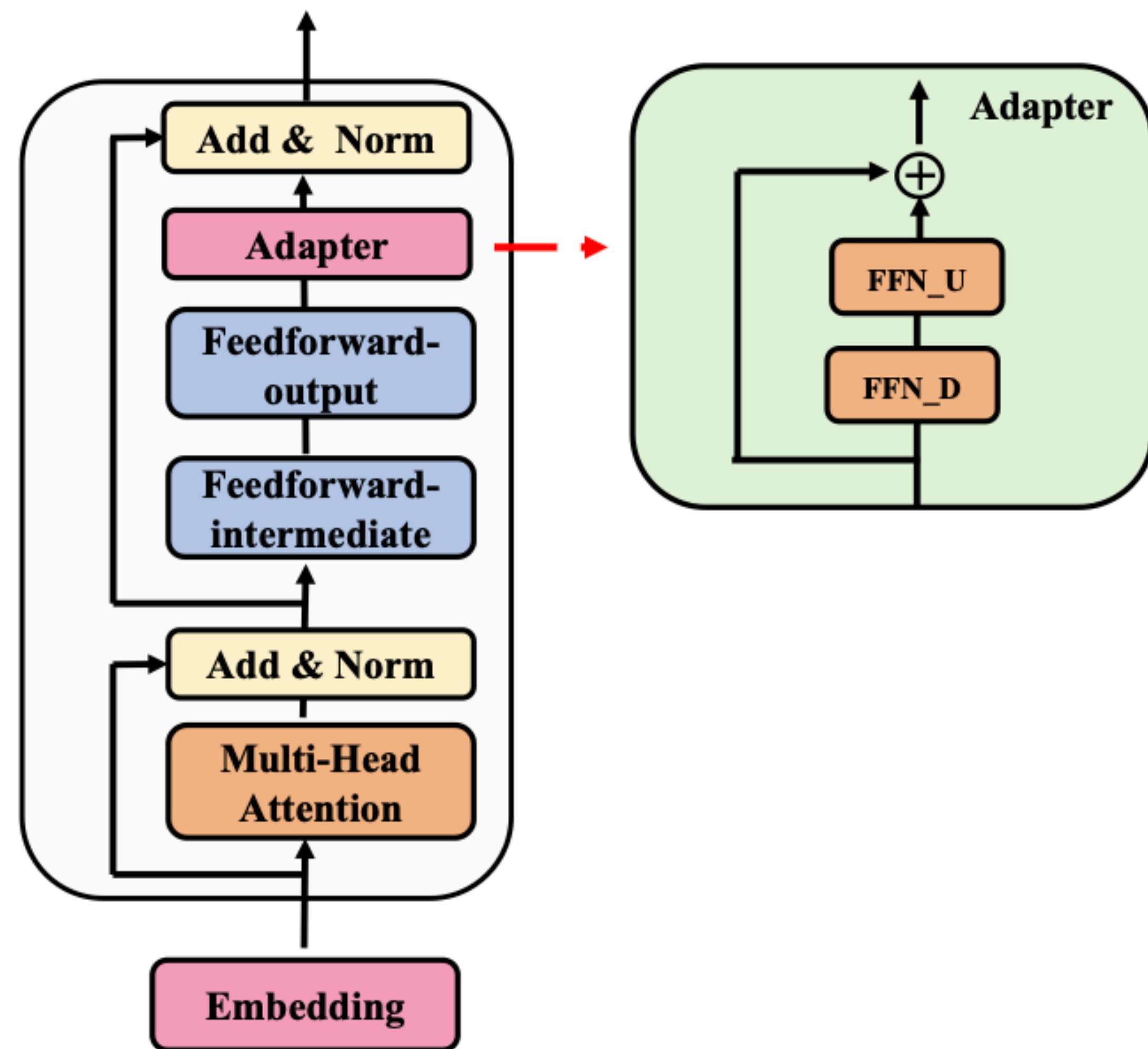
	CoLA	RTE	MRPC	STS-B	CoNLL2003
PASTA	65.4	76.2	89.7	90.8	94.0
- w/o [CLS]	58.8	72.6	91.4	90.2	93.7
- w/o [SEP]	64.5	71.1	91.9	90.3	93.7
- shared vector	64.7	74.7	92.1	90.0	93.9
- classifier only	36.5	54.2	81.5	64.9	77.4

Table 4: Performance of ablation study with BERT-large on GLUE and CoNLL2003 development sets.

Adapters

Bottleneck Adapters

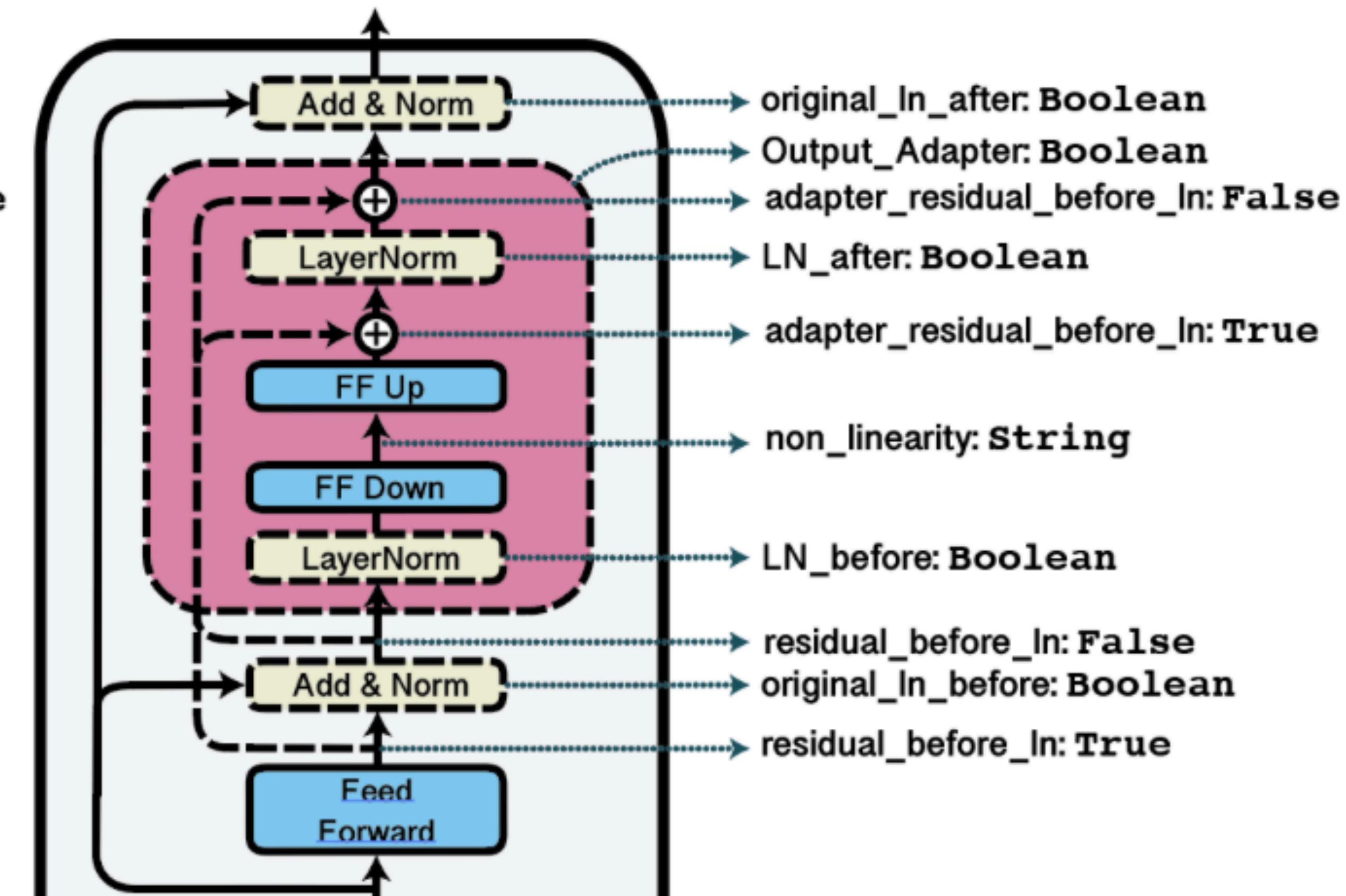
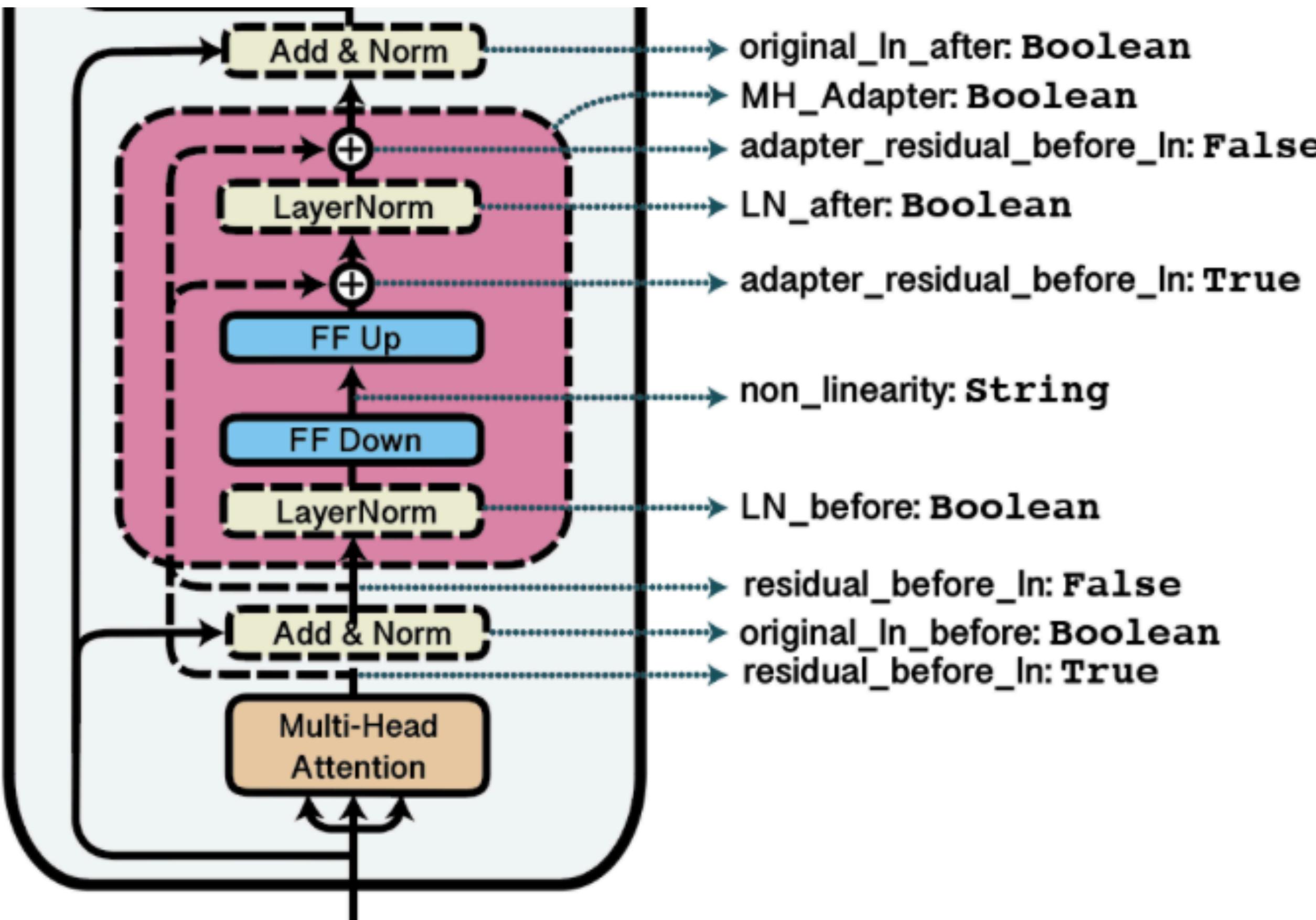
- Given a hidden layer h^ℓ for layer ℓ in a Transformer layer (before Add & Norm)
- $$h^\ell \leftarrow h^\ell + f(h^\ell \cdot W_{\text{down}}) \cdot W_{\text{up}}$$
- W_{down} lowers the dimensionality from $\dim(h^\ell)$ down to k where $k \ll \dim(h^\ell)$
- W_{up} raises the dimensionality from k back up to $\dim(h^\ell)$
- f is a non-linear function (GeLU)
- $$h^{\ell+1} = \text{Add+LN}(h^\ell)$$



<https://arxiv.org/abs/2205.12410>

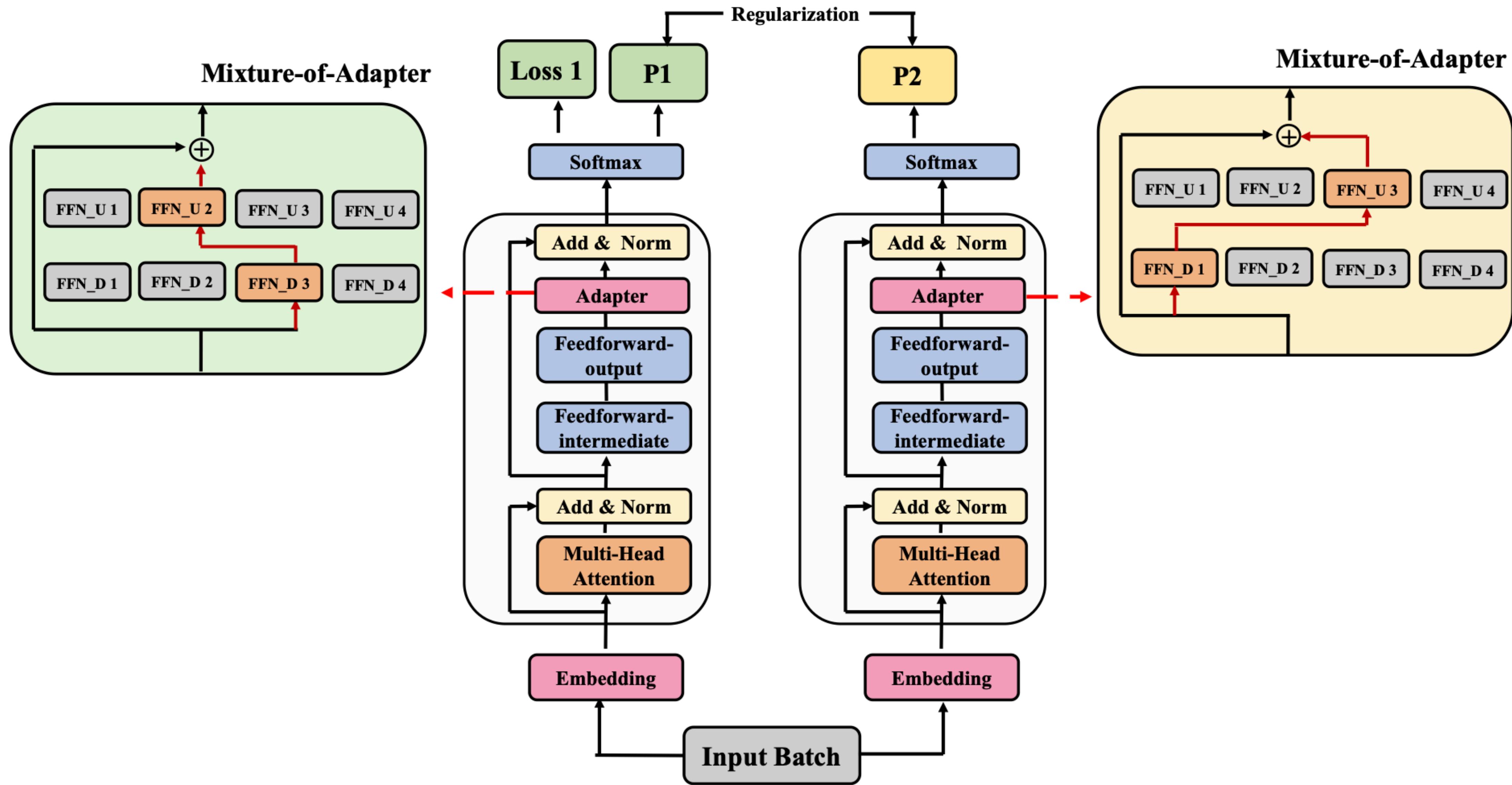
Also see: <https://www.cs.huji.ac.il/labs/learning/Papers/allerton.pdf>

Bottleneck Adapters



Mixture of Adapters

<https://arxiv.org/abs/2205.12410>



Mixture of Adapters

Regularization loss

- For each layer ℓ use M different feed-forward networks for projecting down to k and for projecting up to $\dim(h^\ell)$
- $A_\ell = \{W_{\text{down}}^{\ell,j}, W_{\text{down}}^{\ell,k}\}$ and $B_\ell = \{W_{\text{up}}^{\ell,j}, W_{\text{up}}^{\ell,k}\}$
- where $j, k \in [0, M - 1]$
- $$h^\ell \leftarrow h^\ell + f(h^\ell \cdot W_{\text{down}}^{\ell,i}) \cdot W_{\text{up}}^{\ell,j}$$
- Pick i, j at random
- Pick i, j twice for each input batch.

Mixture of Adapters

Regularization loss

- Fine tuning loss: $\mathcal{L} = - \sum_{c=1}^C \delta(x, \hat{x}) \log \text{softmax}(z^{\mathcal{A}}(x))$
- where δ is 1 if the two arguments are equal
- \hat{x} is the right answer for input x
- $z^{\mathcal{A}}(x)$ are the logits for the fine-tuning output softmax activation (using adapter \mathcal{A})

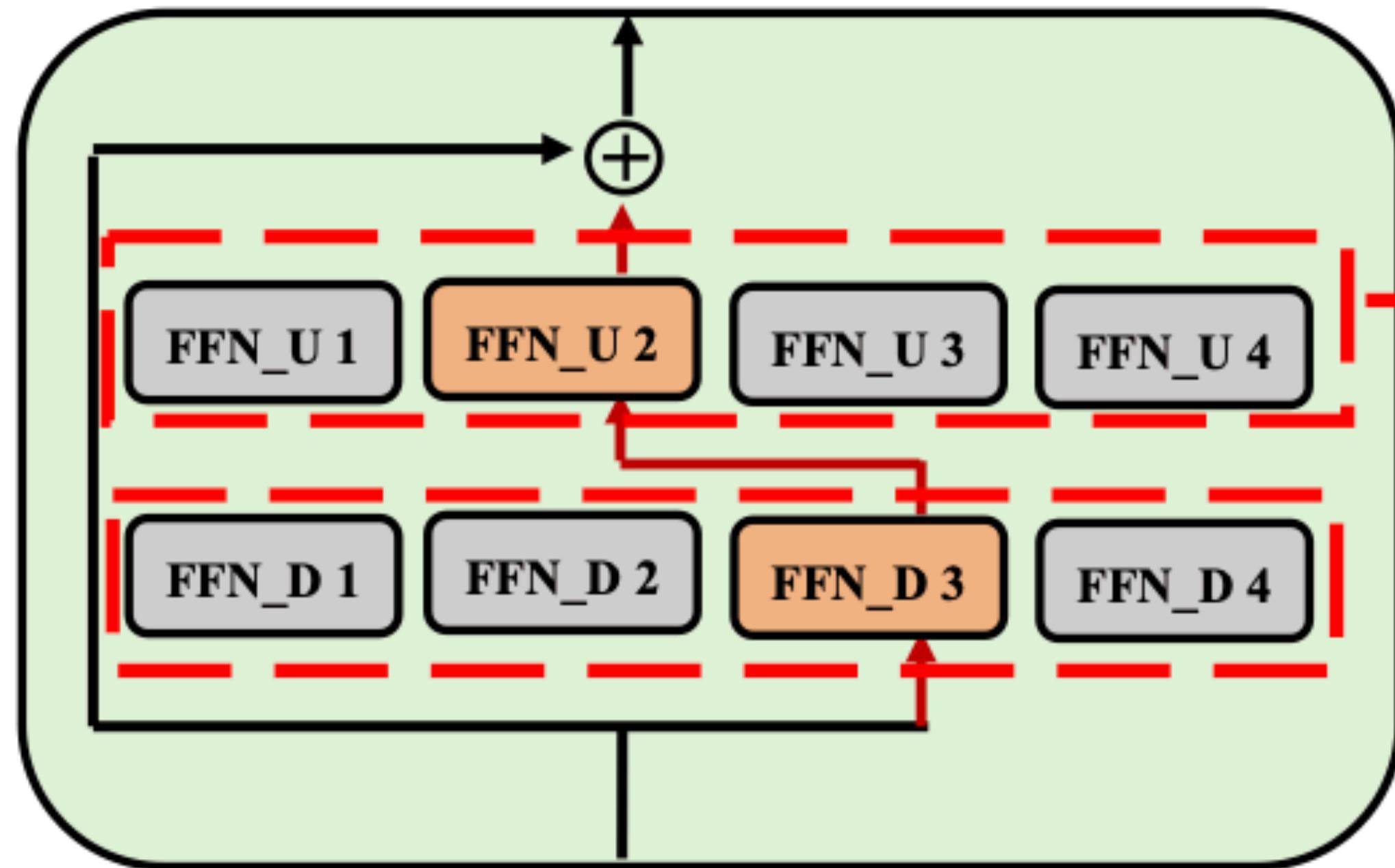
Mixture of Adapters

Regularization loss

- Let $\mathcal{A} = \{A_{\ell=1}^L\}$ and $\mathcal{B} = \{B_{\ell=1}^L\}$ be the adapter modules.
- Pick i, j twice for each input batch.
- Let $D(\mathcal{X}, \mathcal{Y}) = \text{KL}(z^{\mathcal{X}}(x) \| z^{\mathcal{Y}}(x))$ where x is the input to the LLM with frozen parameters; only \mathcal{X}, \mathcal{Y} are trained against fine-tuning prediction loss.
- Add following consistency loss to fine-tuning a LLM
 - $\mathcal{L} \leftarrow \mathcal{L} + \frac{1}{2}(D(\mathcal{A}, \mathcal{B}) + D(\mathcal{B}, \mathcal{A}))$

Mixture of Adapters

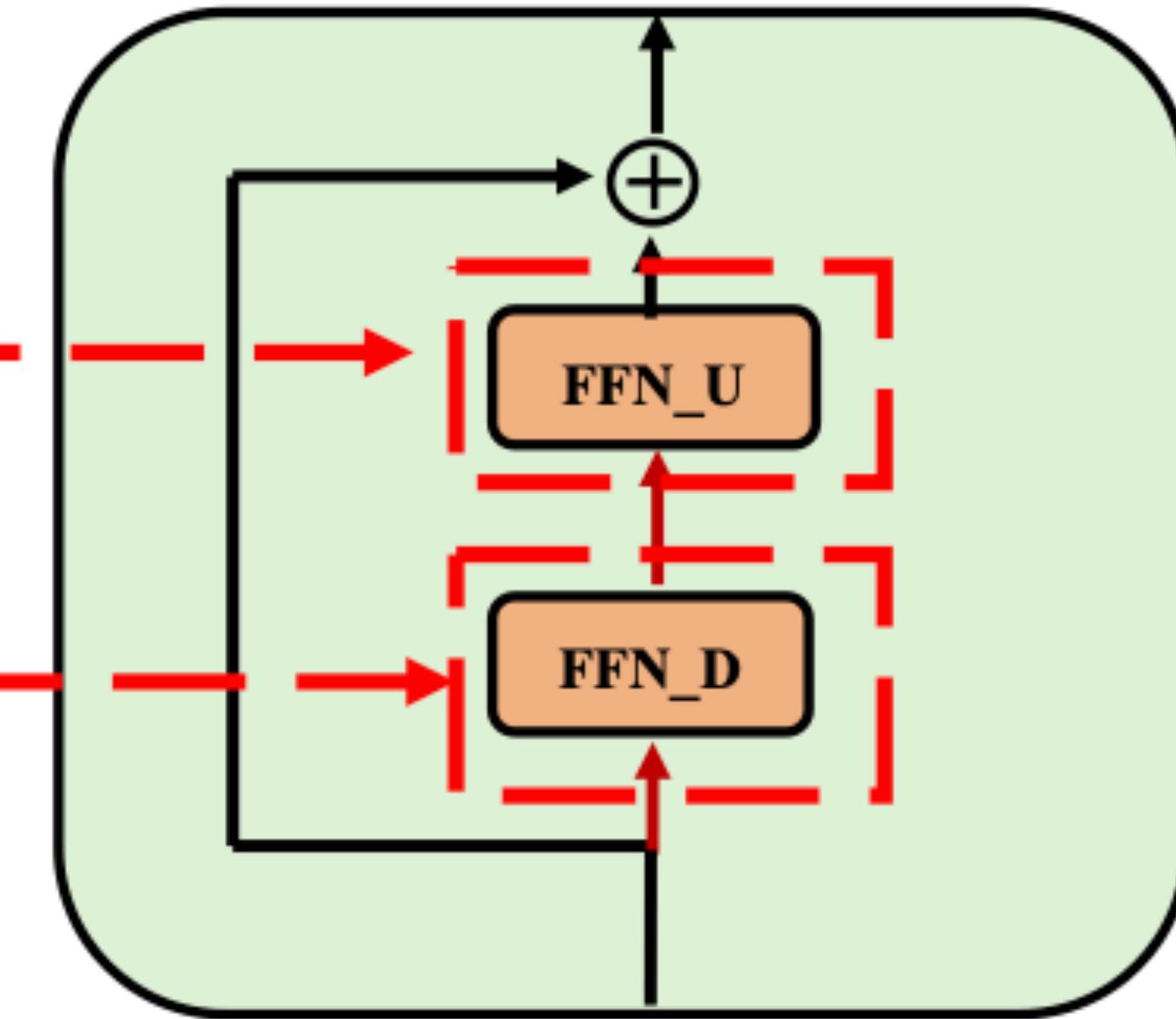
<https://arxiv.org/abs/2205.12410>



Training Stage

$$W_{\text{down}}^{\ell} = \frac{1}{M} \sum_{j=1}^M W_{\text{down}^{\ell,j}}$$

Averaging Weights
of Adapters



Inference Stage

$$W_{\text{up}}^{\ell} = \frac{1}{M} \sum_{j=1}^M W_{\text{up}^{\ell,j}}$$

Results on GLUE with ROBERTa-large

Model	#Param.	MNLI Acc	QNLI Acc	SST2 Acc	QQP Acc	MRPC Acc	CoLA Mcc	RTE Acc	STS-B Pearson	Avg.
Full Fine-tuning [†]	355.0M	90.2	94.7	96.4	92.2	90.9	68.0	86.6	92.4	88.9
Pfeiffer Adapter [†]	3.0M	90.2	94.8	96.1	91.9	90.2	68.3	83.8	92.1	88.4
Pfeiffer Adapter [†]	0.8M	90.5	94.8	96.6	91.7	89.7	67.8	80.1	91.9	87.9
Houlsby Adapter [†]	6.0M	89.9	94.7	96.2	92.1	88.7	66.5	83.4	91.0	87.8
Houlsby Adapter [†]	0.8M	90.3	94.7	96.3	91.5	87.7	66.3	72.9	91.5	86.4
LoRA [†]	0.8M	90.6	94.8	96.2	91.6	90.2	68.2	85.2	92.3	88.6
AdaMix Adapter	0.8M	90.9	95.4	97.1	92.3	91.9	70.2	89.2	92.4	89.9

Results on GLUE with BERT-base

Model	#Param.	Avg.
Full Fine-tuning [†]	110M	82.7
Houlsby Adapter [†]	0.9M	83.0
BitFit [◊]	0.1M	82.3
Prefix-tuning [†]	0.2M	82.1
LoRA [†]	0.3M	82.2
UNIPELT (AP) [†]	1.1M	83.1
UNIPELT (APL) [†]	1.4M	83.5
AdaMix Adapter	0.9M	84.5

Results on E2E with GPT2-medium

Model	#Param.	BLEU	NIST	MET	ROUGE-L	CIDEr
Full Fine-tuning [†]	354.92M	68.2	8.62	46.2	71.0	2.47
Lin AdapterL [†]	0.37M	66.3	8.41	45.0	69.8	2.40
Lin Adapter [†]	11.09M	68.9	8.71	46.1	71.3	2.47
Houlsby Adapter [†]	11.09M	67.3	8.50	46.0	70.7	2.44
FT ^{T op2} [†]	25.19M	68.1	8.59	46.0	70.8	2.41
PreLayer [†]	0.35M	69.7	8.81	46.1	71.4	2.49
LoRA [†]	0.35M	70.4	8.85	46.8	71.8	2.53
LoRA (repr.)	0.35M	69.8	8.77	46.6	71.8	2.52
AdaMix Adapter	0.42M	69.8	8.75	46.8	71.9	2.52
AdaMix LoRA	0.35M	71.0	8.89	46.8	72.2	2.54

Simple, Scalable Adaptation for Neural Machine Translation

Ankur Bapna

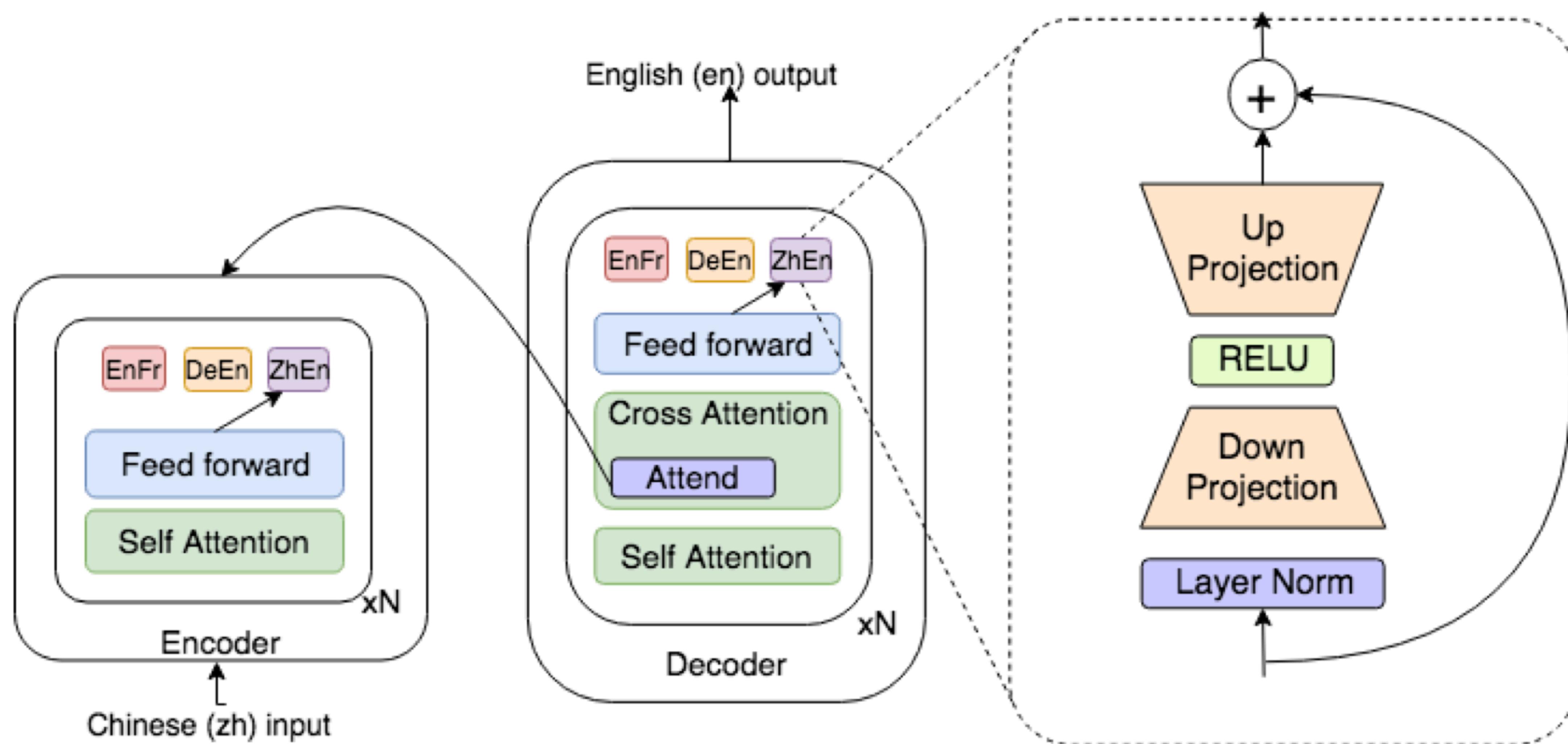
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<https://arxiv.org/abs/1909.08478>



LORA: LOW-RANK ADAPTATION OF LARGE LANGUAGE MODELS

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Yelong Shen*

Shean Wang

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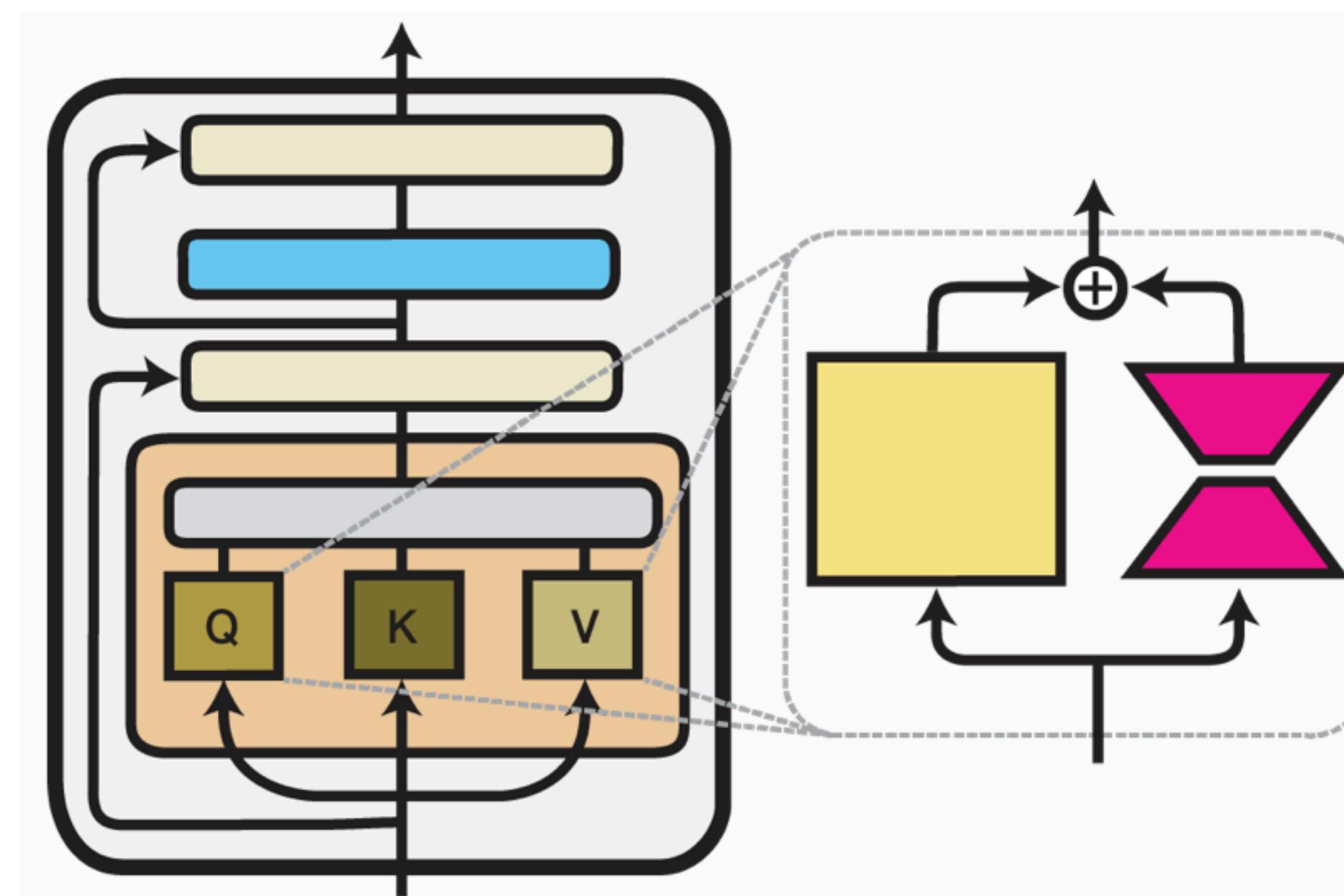
Lu Wang

Zeyuan Allen-Zhu

Weizhu Chen

LoRA

- Can be applied to any Transformer-based Large Language Model
- But specifically designed for autoregressive and causal LMs like GPTx
- Just like other Transformer adapters, LoRA adds a small set of parameters for fine-tuning and keeps the original parameters frozen
- This can help a lot when LLM parameter sizes are as large as 175 billion.

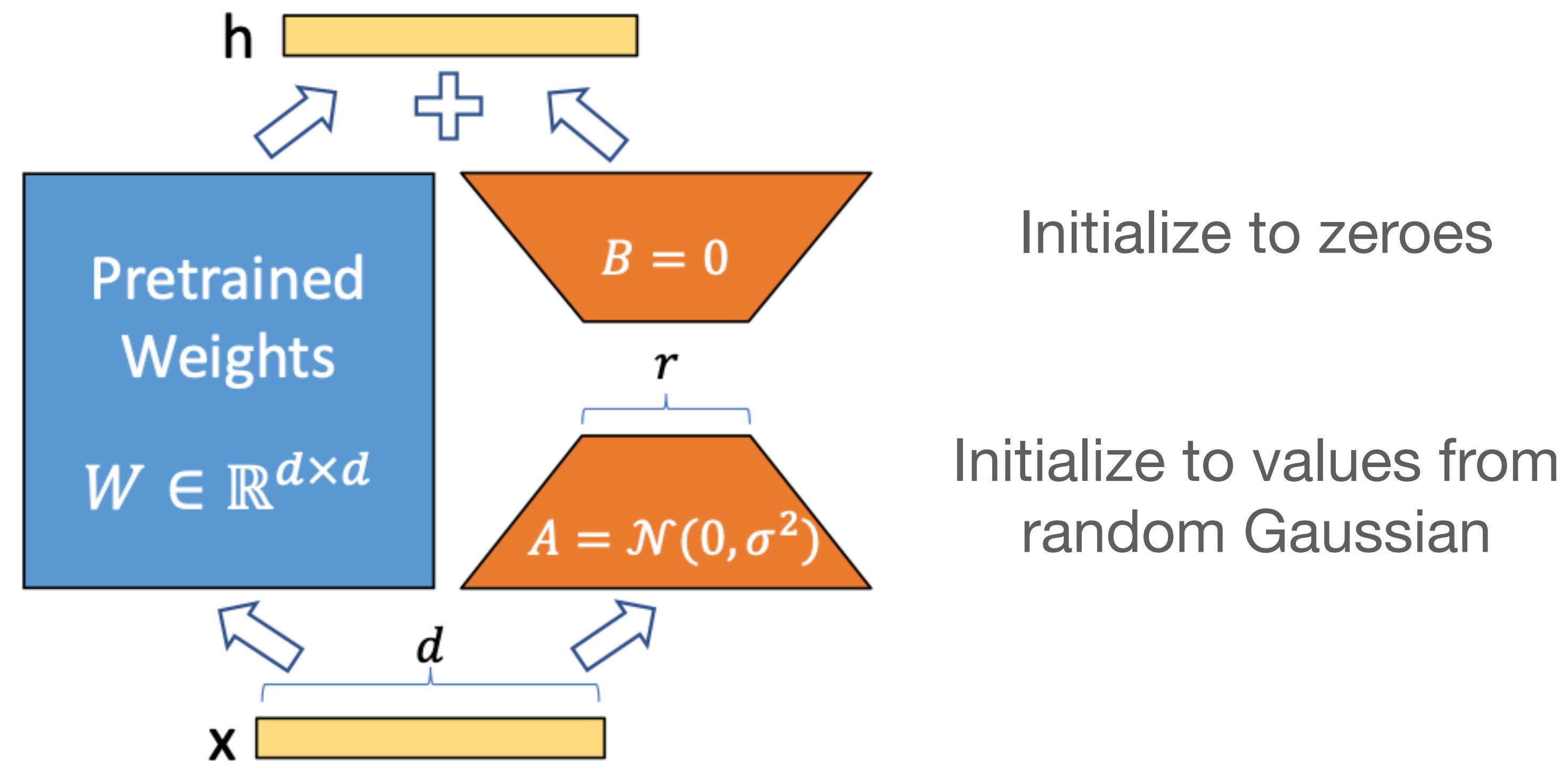


LoRA

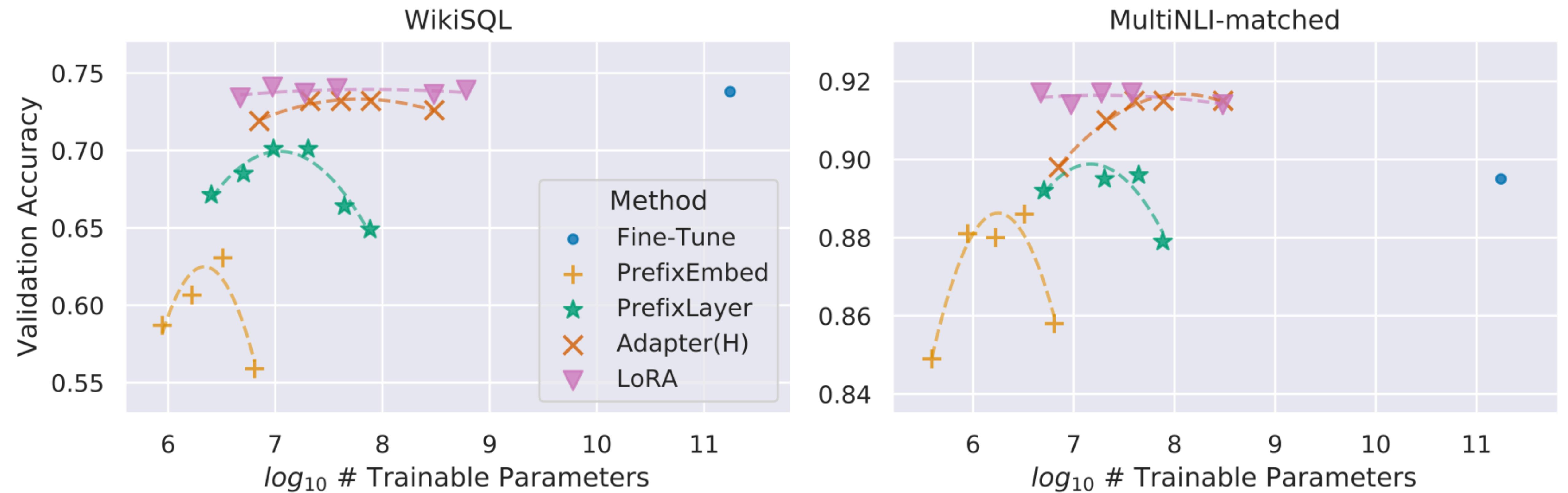
- Only use adapters in the attention matrices: Q, K, V
- Each matrix is called W_p here, p for pre-trained
- Adapter methods modify W_p to be $W_p + BA$ where $B \in \mathbb{R}^{d \times r}, A \in \mathbb{R}^{r \times k}$
- Rank $r \ll \min(d, k)$
- Let BA be zero at start of training
 - Scale the parameters after backpropagation by $\frac{\alpha}{r}$ where α is a hyperparameter set to a constant value depending on r (set to the first r in training)

LoRA

- Initialize B to zeroes
- Initialize A using random Gaussian initialization



Model & Method	# Trainable Parameters	E2E NLG Challenge					CIDEr
		BLEU	NIST	MET	ROUGE-L		
GPT-2 M (FT)*	354.92M	68.2	8.62	46.2	71.0	2.47	
GPT-2 M (Adapter ^L)*		66.3	8.41	45.0	69.8	2.40	
GPT-2 M (Adapter ^L)*		68.9	8.71	46.1	71.3	2.47	
GPT-2 M (Adapter ^H)		67.3 _{±.6}	8.50 _{±.07}	46.0 _{±.2}	70.7 _{±.2}	2.44 _{±.01}	
GPT-2 M (FT ^{Top2})*		68.1	8.59	46.0	70.8	2.41	
GPT-2 M (PreLayer)*		69.7	8.81	46.1	71.4	2.49	
GPT-2 M (LoRA)		70.4 _{±.1}	8.85 _{±.02}	46.8 _{±.2}	71.8 _{±.1}	2.53 _{±.02}	
GPT-2 L (FT)*	774.03M	68.5	8.78	46.0	69.9	2.45	
GPT-2 L (Adapter ^L)		69.1 _{±.1}	8.68 _{±.03}	46.3 _{±.0}	71.4 _{±.2}	2.49 _{±.0}	
GPT-2 L (Adapter ^L)		68.9 _{±.3}	8.70 _{±.04}	46.1 _{±.1}	71.3 _{±.2}	2.45 _{±.02}	
GPT-2 L (PreLayer)*		70.3	8.85	46.2	71.7	2.47	
GPT-2 L (LoRA)		70.4 _{±.1}	8.89 _{±.02}	46.8 _{±.2}	72.0 _{±.2}	2.47 _{±.02}	



GPT-3 175B validation accuracy vs. number of trainable parameters