

# SAMformer: Unlocking the Potential of Transformers in Time Series Forecasting

Ambroise Odonnat  
Huawei Noah's Ark Lab

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école —————  
normale —————  
supérieure —————  
paris-saclay —————



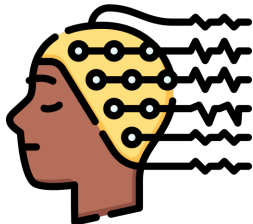
- ① Introduction
- ② Failure of Transformers
- ③ SAMformer
- ④ Experiments
- ⑤ Take Home Message



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- 2 Failure of Transformers
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- 5 Take Home Message



In many applications, data are gathered sequentially.





Goal → Analysing time series data to predict future trends.

- Forecast of ECG recording to predict cardiac arrhythmia,
- Electricity consumption forecasting to match future demand,
- Predicting stock market prices.

Challenges

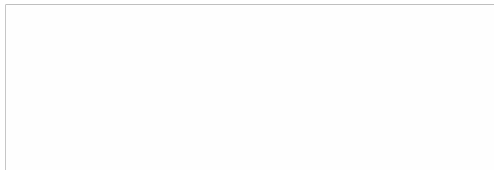
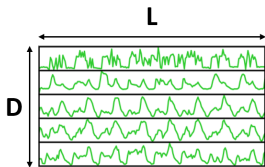
- ① Long-term temporal dependencies,
- ② Highly correlated features.



$D$ -dimensional time series of length  $L \rightarrow$  predict next  $H$  values.

- Training set of  $N$  observations ( $\{\mathbf{X}^{(i)}\}_{i=0}^N, \{\mathbf{Y}^{(i)}\}_{i=0}^N$ ),
- Find predictor  $f_{\omega}: \mathbb{R}^{D \times L} \rightarrow \mathbb{R}^{D \times H}$  that minimizes the MSE

$$\mathcal{L}_{\text{train}}(\omega) = \frac{1}{ND} \sum_{i=0}^N \|\mathbf{Y}^{(i)} - f_{\omega}(\mathbf{X}^{(i)})\|_F^2.$$

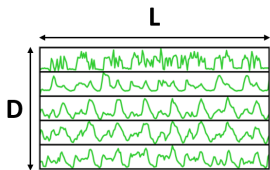




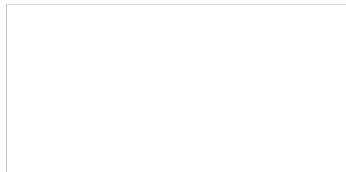
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Model

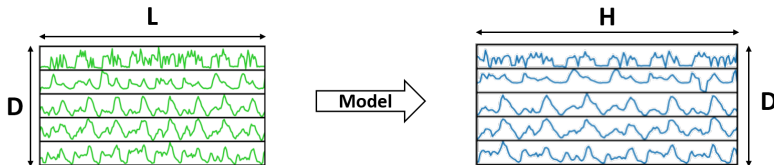




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## Standard methods:

- AR models (ARIMA)
- Seasonal naive

## Deep learning methods

- RNN, CNN
- Transformer-based models



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## Motivation

- Transformers tailored to deal with sequential data,
- Impressive results in NLP and Computer Vision.

## Main challenges

- ① Quadratic computation of self-attention,
- ② Complex long-term dependencies.



## Main challenges

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## Main challenges

- ① Quadratic complexity of self-attention
  - Sparse attention: LogTrans [5], Informer [13]
  - Modified attention: Pyraformer [6]
- ② Complex long-term dependencies
  - Decomposition scheme: Autoformer [10], Pyraformer [6]
  - Fourier domain: FEDformer [14]

**It leads to a wide range of Anything-formers with heavy and complex implementation and many parameters.**



[11] showed that linear models outperform SOTA Anything-former.

**Transformers in  
Computer Vision and NLP**



**Commander of the Armies of GPT,  
General of the Gemini Legions, loyal  
servant to Claude, Llama3, Mixtral**

**Transformers in Time  
Series Forecasting**



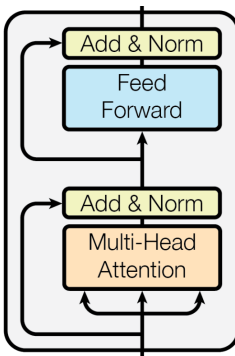
**Please help, I just got  
beaten by a linear model**



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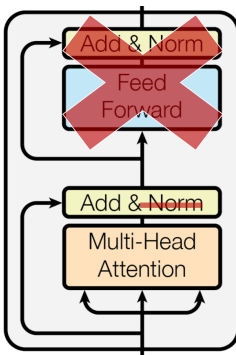
- Generate toy data according to  $\mathbf{Y} = \mathbf{X}\mathbf{W}_{\text{toy}} + \epsilon$ ,
- Designing the simplest Transformer possible.







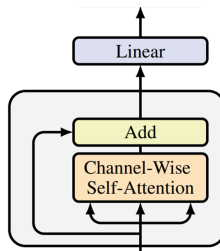
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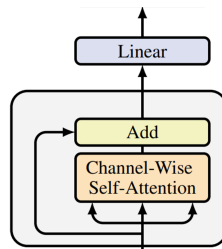
$$\mathbf{A}(\mathbf{X}) = \text{softmax}\left(\frac{\mathbf{X}\mathbf{W}_Q\mathbf{W}_K^T\mathbf{X}^T}{\sqrt{d_m}}\right)$$
$$f(\mathbf{X}) = [\mathbf{X} + \mathbf{A}(\mathbf{X})\mathbf{X}\mathbf{W}_V\mathbf{W}_O]\mathbf{W}$$





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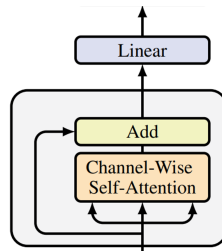
Theorem (Ilbert, O., Feofanov et al.)

Given fixed attention weights  $\mathbf{W}_Q, \mathbf{W}_K, \mathbf{W}_V, \mathbf{W}_O$ , there exists an infinity of optimal  $\mathbf{W}$  reaching the oracle, i.e.,  $f(\mathbf{X}) = \mathbf{X}\mathbf{W}_{\text{toy}}$ .



- Generate toy data according to  $\mathbf{Y} = \mathbf{X}\mathbf{W}_{\text{toy}} + \varepsilon$ ,
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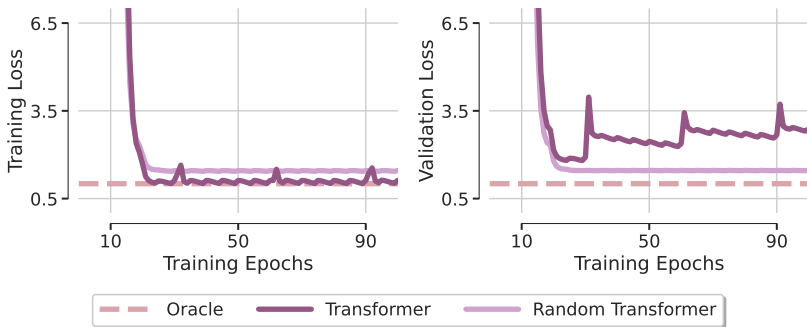
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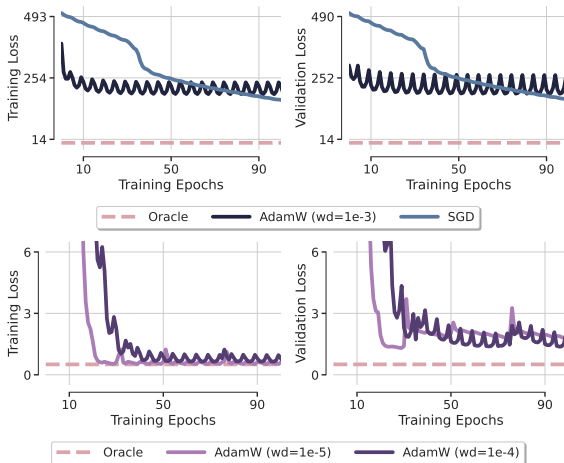
**In theory, our simplistic Transformer can be optimal. Is this the case in practice?**



- Oracle: optimal solution,
- Transformer with  $\mathbf{W}_Q, \mathbf{W}_K, \mathbf{W}_V, \mathbf{W}_O, \mathbf{W}$  trainable,
- Random Transformer: only  $\mathbf{W}$  is trainable.



Despite its simplicity, Transformer overfits a lot. Fixing the attention weight improves generalization.

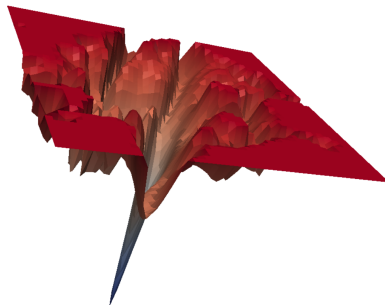


Poor generalization of Transformer with SGD, Adam, and AdamW.



## Hypothesis from NLP and Computer Vision

- Transformers have **sharp loss landscape** [2]
  - Convergence to sharp minima  $\rightarrow$  poor generalization,
  - Computed as  $\lambda_{\max}$ , the largest singular value of the Hessian.



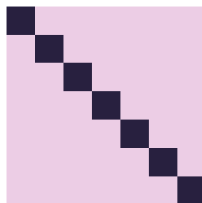


## Hypothesis from NLP and Computer Vision

- Transformers have **sharp loss landscape** [2],
- Attention suffers from **entropy collapse** [12].
  - Entropy = average entropy of the rows,
  - It causes training instability,
  - [12] → entropy collapse and sharpness appear in tandem.



~ Uniform → high entropy.



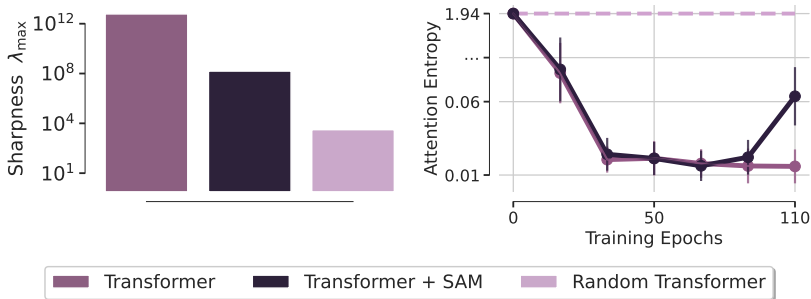
Diagonal → low entropy.





## Hypothesis from NLP and Computer Vision

- Transformers have **sharp loss landscape** [2],
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Training the attention induces an entropy collapse and a sharp loss landscape.



## ① $\sigma$ Reparam [12]

Replace each weight matrix  $\mathbf{W}$  by

$$\widehat{\mathbf{W}} = \frac{\gamma}{\|\mathbf{W}\|_2} \mathbf{W}, \text{ with } \gamma \in \mathbb{R} \text{ learnable,}$$

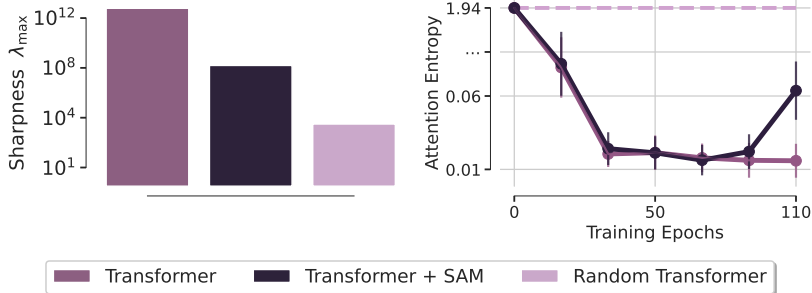
## ② Sharpness-Aware Minimization (SAM) [3]

Replace the training loss  $\mathcal{L}_{\text{train}}$  by

$$\mathcal{L}_{\text{train}}^{\text{SAM}}(\boldsymbol{\omega}) = \max_{\|\boldsymbol{\varepsilon}\| < \rho} \mathcal{L}_{\text{train}}(\boldsymbol{\omega} + \boldsymbol{\varepsilon}) \approx \mathcal{L}_{\text{train}}\left(\boldsymbol{\omega} + \rho \cdot \frac{\nabla \mathcal{L}_{\text{train}}(\boldsymbol{\omega})}{\|\nabla \mathcal{L}_{\text{train}}(\boldsymbol{\omega})\|_2}\right).$$



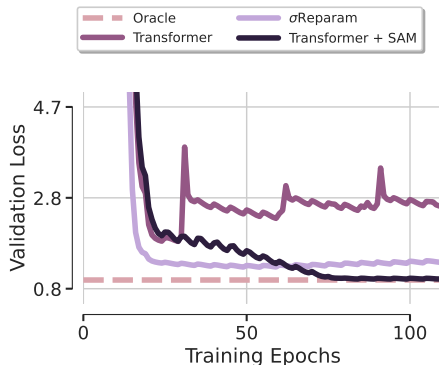
Contrary to NLP and Computer Vision, entropy collapse seems benign in time series forecasting while sharpness is harmful.



# $\sigma$ Reparam doesn't solve the problem, but SAM does.



Contrary to NLP and Computer Vision, entropy collapse seems benign in time series forecasting while sharpness is harmful.



$\sigma$ Reparam helps but is not sufficient while using SAM leads to the optimal solution (oracle).

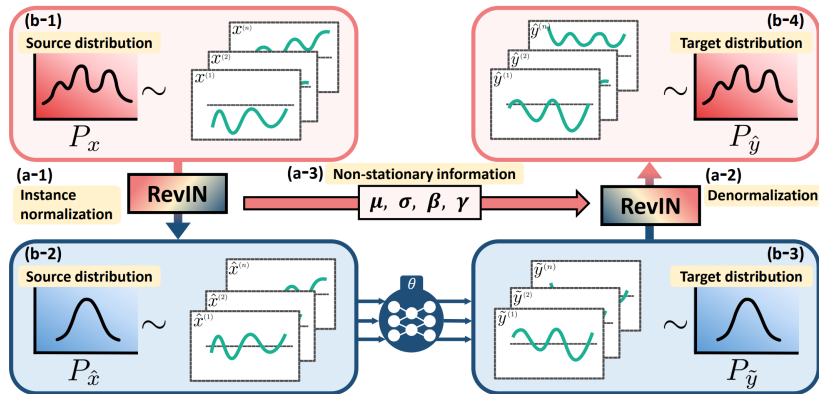


RevIN [4] → Reduce distribution shift between input and target.

- Multivariate time series  $\mathbf{X} \in \mathbb{R}^{D \times L}$ , learnable  $\gamma, \beta$ .
- Normalize each feature  $\mathbf{X}_i \leftarrow \tilde{\mathbf{X}}_i = \frac{\mathbf{X}_i - \mu}{\sigma} \leftarrow \gamma \tilde{\mathbf{X}}_i + \beta$ ,
- Apply model on multivariate time series  $\tilde{\mathbf{Y}} = f(\tilde{\mathbf{X}})$ ,
- Denormalize each feature  $\tilde{\mathbf{Y}}_i \leftarrow \hat{\mathbf{Y}}_i = \frac{\tilde{\mathbf{Y}}_i - \beta}{\gamma} \leftarrow \sigma \hat{\mathbf{Y}}_i + \mu$ .



RevIN [4] → Reduce distribution shift between input and target.

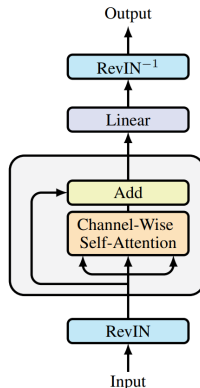




- Input  $\mathbf{X} \in \mathbb{R}^{D \times L}$ , output  $f(\mathbf{X}) \in \mathbb{R}^{D \times H}$ ,
- Reduce distribution shift with **RevIN** [4],
- **Channel-wise attention**  $\mathbf{A}(\mathbf{X}) \in \mathbb{R}^{D \times D}$ ,
- **Smooth** loss landscape with SAM [3].

$$\mathbf{A}(\mathbf{X}) = \text{softmax}\left(\frac{\mathbf{X}\mathbf{W}_Q\mathbf{W}_K^\top\mathbf{X}^\top}{\sqrt{d_m}}\right)$$

$$f(\mathbf{X}) = [\mathbf{X} + \mathbf{A}(\mathbf{X})\mathbf{X}\mathbf{W}_V\mathbf{W}_O]\mathbf{W}$$



**SAMformer** is a shallow transformer trained with SAM.  
 → One head, one encoder, 15 lines of code!



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All-MLP model (2023): TSMixer [1].

Transformers (2021-2022): FEDformer [14], Autoformer [10].

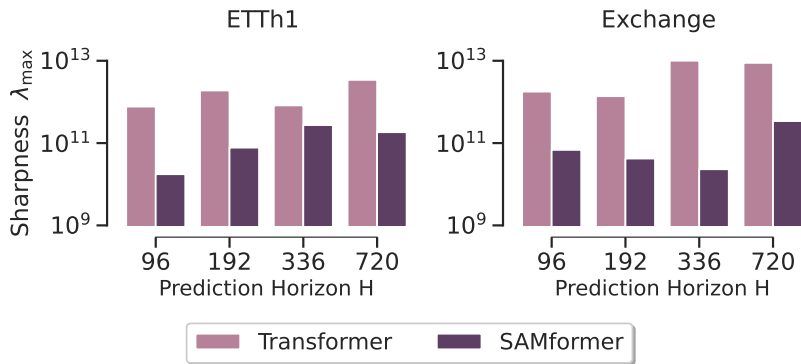
Recent Transformers (2023-2024): iTransformer [7], PatchTST [8].

Dataset	ETTh1/ETTh2	ETTM1/ETTM2	Electricity	Exchange	Traffic	Weather
# features	7	7	321	8	862	21
# time steps	17420	69680	26304	7588	17544	52696
Granularity	1 hour	15 minutes	1 hour	1 day	1 hour	10 minutes



Dataset	<b>SAMformer</b>	iTransformer	PatchTST	TSMixer	FEDformer	Autoformer
	-	2024	2023	2023	2022	2021
ETTh1	<b>0.410</b>	0.454	0.469	0.437	0.440	0.496
ETTh2	<b>0.344</b>	0.383	0.387	0.357	0.437	0.450
ETTm1	<b>0.373</b>	0.407	0.387	0.385	0.448	0.588
ETTm2	<b>0.269</b>	0.288	0.281	0.289	0.305	0.327
Traffic	<b>0.425</b>	0.428	0.481	0.620	0.610	0.628
Weather	0.260	<b>0.258</b>	0.259	0.267	0.309	0.338
<b>Overall improvement</b>		<b>6.58%</b>	<b>8.79%</b>	<b>13.2%</b>	<b>22.5%</b>	<b>35.9%</b>

**SAMformer outperforms all baselines while having significantly fewer parameters.**



**SAM provides a smoother loss landscape ...**



... leading to better generalization and robustness.



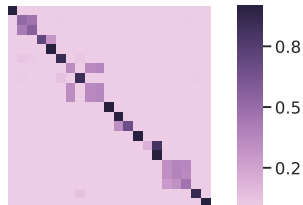
Transformer



$\sigma$ Reparam



SAMformer



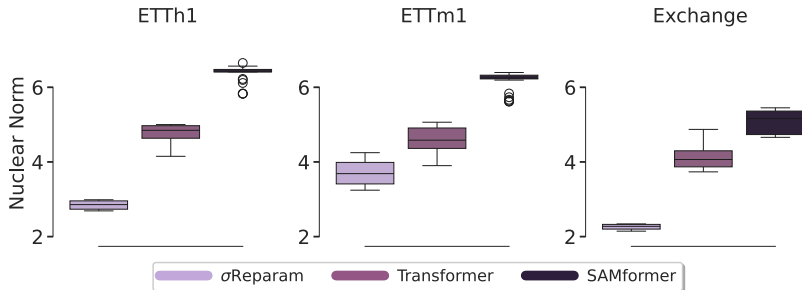
**Channel-wise attention improves the propagation of the signal with self-feature correlations as in ViTs.**



Theorem (Ilbert, O., Feofanov et al.)

Applying  $\sigma$ Reparam [12] leads to **attention rank collapse**.

$$\|\mathbf{X}\mathbf{W}_Q\mathbf{W}_K^T\mathbf{X}^T\|_* \leq \underbrace{\|\mathbf{W}_Q\mathbf{W}_K^T\|_2}_{\text{goes to 0 with } \sigma\text{Reparam}} \|\mathbf{X}\|_F^2.$$





- MOIRAI [9]: foundation model trained on **27B samples**,
- Nb. params: small (**14M**), base (**91M**) and large (**314M**).

Dataset	Full-shot	Zero-shot		
	<b>SAMformer</b>	MOIRAI <sub>Small</sub>	MOIRAI <sub>Base</sub>	MOIRAI <sub>Large</sub>
ETTh1	<u>0.410</u>	<b>0.400</b>	0.434	0.510
ETTh2	<u>0.344</u>	<b>0.341</b>	0.345	0.354
ETTm1	<b>0.373</b>	0.448	<u>0.381</u>	0.390
ETTm2	<b>0.269</b>	0.300	<u>0.272</u>	0.276
Electricity	<b>0.181</b>	0.233	<u>0.188</u>	<u>0.188</u>
Weather	0.260	<u>0.242</u>	<b>0.238</b>	0.259
<b>Overall MSE improvement</b>		<b>6.9%</b>	<b>1.1%</b>	<b>7.6%</b>

**SAMformer outperforms MOIRAI while having significantly fewer parameters!**



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## Findings

- Transformer failure → trainability issues of the attention,
- In time series forecasting, entropy collapse is benign,
- But sharpness prevents good generalization.

## Proposal

- **SAMformer**: RevIN + channel-wise attention + SAM,
- SOTA and lightest model,
- Strong competitor to MOIRAI [9].



This work has been accepted as an **Oral at ICML 2024, Vienna**. You may find the links to the paper and the code below. To know more about my research, check my website: [ambroiseodt.github.io](https://ambroiseodt.github.io) and feel free to contact me.

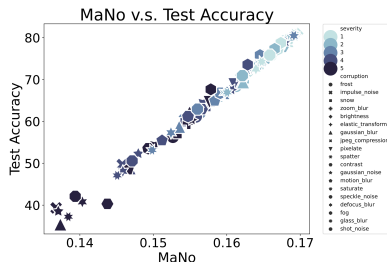
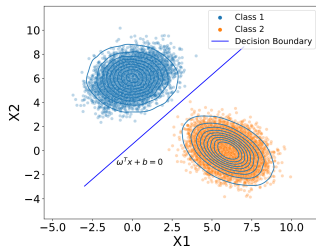
- ★ Paper: <https://arxiv.org/pdf/2402.10198>
- ★ Code: <https://github.com/romilbert/samformer>



This project was led by [Romain Ilbert](#) and [myself](#) with our co-authors [Vasilii Feofanov](#), [Aladin Virmaux](#), [Giuseppe Paolo](#), [Themis Palpanas](#), and [Ievgen Redko](#).



## MANO: Exploiting Matrix Norm for Unsupervised Accuracy Estimation Under Distribution Shifts



<https://arxiv.org/pdf/2405.18979>

Thanks for your attention !



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- [10] Wu, H., Xu, J., Wang, J., and Long, M. (2021). Autoformer: Decomposition transformers with Auto-Correlation for long-term series forecasting. In *Advances in Neural Information Processing Systems*.
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- [12] Zhai, S., Likhomanenko, T., Littwin, E., Busbridge, D., Ramapuram, J., Zhang, Y., Gu, J., and Susskind, J. M. (2023). Stabilizing transformer training by preventing attention entropy collapse. In Krause, A., Brunskill, E., Cho, K., Engelhardt, B., Sabato, S., and Scarlett, J., editors, *Proceedings of the 40th International Conference on Machine Learning*, volume 202 of *Proceedings of Machine Learning Research*, pages 40770–40803. PMLR.
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- [14] Zhou, T., Ma, Z., Wen, Q., Wang, X., Sun, L., and Jin, R. (2022). FEDformer: Frequency enhanced decomposed transformer for long-term series forecasting. In *Proc. 39th International Conference on Machine Learning (ICML 2022)*.