

CRaSh: Clustering, Removing, and Sharing Enhance Fine-tuning without Full Large Language Model

Kaiyan Zhang¹, Ning Ding^{1,2}, Biqing Qi^{1,2,3}, Xuekai Zhu¹
Xinwei Long¹, Bowen Zhou^{1,2*}

¹ Department of Electronic Engineering, Tsinghua University, Beijing, China

² Frontis.AI, Beijing, China

³ School of Astronautics, Harbin Institute of Technology, Harbin, China

zhang-ky22@mails.tsinghua.edu.cn

zhoubowen@tsinghua.edu.cn

Abstract

Instruction tuning has recently been recognized as an effective way of aligning Large Language Models (LLMs) to enhance their generalization ability across various tasks. However, when tuning publicly accessible, centralized LLMs with private instruction data, privacy concerns are inevitable. While direct transfer of parameterized modules between models is a plausible approach to address this, its implications and effectiveness need further exploration. This paper focuses on Offsite-Tuning (OFT), a representative technique that transfers transformer blocks between centralized LLMs and downstream emulators. Given the limited understanding of the underlying mechanism of OFT, we perform an empirical analysis on LLMs from the perspectives of representation and functional similarity. Interestingly, our findings reveal a unique modular structure within the layers of LLMs that appears to emerge as the model size expands. Simultaneously, we note subtle but potentially significant changes in representation and intermediate predictions across the layers. Inspired by these observations, we propose CRaSh, involving Clustering, Removing, and Sharing, a training-free strategy to derive improved emulators from LLMs. CRaSh significantly boosts performance of OFT with billions of parameters. Furthermore, we investigate the optimal solutions yielded by fine-tuning with and without full model through the lens of loss landscape. Our findings demonstrate a linear connectivity among these optima falling over the same basin, thereby highlighting the effectiveness of CRaSh and OFT. The source code is publicly available at <https://github.com/TsinghuaC3I/CRaSh>.

1 Introduction

Nowadays, there is a growing interest in large language models (LLMs) such as PaLM (Chowdhery et al., 2022), LLaMA (Touvron et al., 2023) and

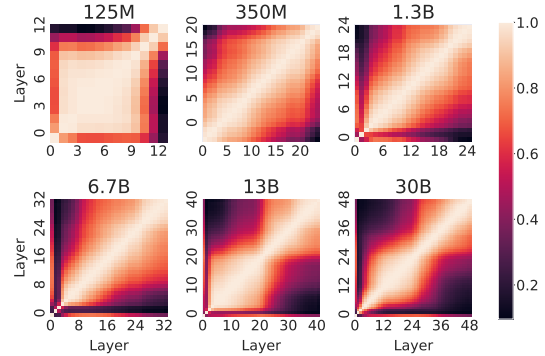


Figure 1: Emergence of modular structure of representations of LLMs. The table displays representation similarity among layers of OPT models (Zhang et al., 2022) on ARC dataset (Clark et al., 2018) with instruction format. The lighter colors indicate higher similarity and same color scale is used in all plots.

GPT-4 (OpenAI, 2023) due to their potential towards advanced intelligent systems. By employing techniques like prompt learning (Ding et al., 2022a; Wei et al., 2022b) and instruction tuning (Sanh et al., 2022; Wei et al., 2022a; Wang et al., 2022b,c), the behavior of LLMs can be aligned with human intent using a small amount of data. (Taori et al., 2023; Chiang et al., 2023; Zhou et al., 2023).

However, the centralization of LLMs poses a significant challenge concerning the trade-off between high performance and user data (Li et al., 2022a). For instance, OpenAI provides fine-tuning APIs* that allows users to upload personal data for further fine-tuning of davinci models family, which has gained popularity in the industry, like OpenAI GPT-4 (OpenAI, 2023), Google Bard[†], and Anthropic Claude[‡]. Safeguarding the privacy of both LLMs and downstream user data is an urgent concern. One viable approach involves the direct transfer of parameterized modules between models, such as Federated Learning (FL) (McMahan

*Corresponding author

*<https://platform.openai.com/docs/guides>

[†]<https://bard.google.com/>

[‡]<https://www.anthropic.com/product>

et al., 2017; Lin et al., 2022) and Split Learning (SL) (Vepakomma et al., 2018; Thapa et al., 2022), where limited exploration are conducted on LLMs with billions of parameters. Recently, Xiao et al. (2023) propose Offsite-Tuning (OFT) for transfer learning that operates independently of full LLMs with sizes exceeding 1B. OFT entails compressing the LLM into a smaller model known as emulator by layer dropping, followed by fine-tuning the emulator using user data. Finally, the parameterized modules are transferred from emulator and seamlessly integrated into LLM in a single turn. Despite the promising results obtained by OFT, there is still limited understanding of its underlying mechanism.

In this paper, we conduct a detailed analysis of LLMs from the perspective of representation and functional similarity (Kornblith et al., 2019; Belrose et al., 2023) to enhance our understanding of OFT. Through comparing the similarity of hidden states across layers, we observe *emergence of modular structure* of representations within LLMs. As depicted in Figure 1, models with a size less than 10B exhibit uniform representations across all layers. However, for models of size 13B and 30B, modular structure becomes apparent in the representation similarities. For the 13B model, high similarities are observed between layers 5 and 20, forming a light-colored block-diagonal structure (i.e., *modular structure*), as well as between layers 25 and 40. Additionally, we note subtle changes in the representation between adjacent layers. We further analyze functional similarity to explore the intermediate predictions of each layer, which enhances these findings.

Building upon our findings, we propose a completely training-free strategy to enhance fine-tuning without relying on full model. This strategy consists of three steps, namely Clustering, Removing, and Sharing (CRaSh). In the initial step, we cluster adjacent layers based on their similarity using various hierarchical clustering algorithms (Murtagh and Contreras, 2012). We then remove layers within the same cluster to obtain an emulator. The remaining layers are shared as a supplement to the removed layers. Finally, selected layers of the emulator are updated using downstream data and transferred to be seamlessly integrated into LLMs, resulting in improved performance. Through the utilization of CRaSh, we significantly enhance the performance of fine-tuning LLMs without full models across multiple datasets. In order to comprehend

the relationship of optimal solutions in CRaSh, we visualize the optima using loss surfaces and mode connectivity (Li et al., 2018; Frankle et al., 2020). This study offers valuable insights into the effectiveness of CRaSh. In summary, our main contributions can be summarized as follows:

- We discover emergence of *modular structure* within layers along with size of model increase in decoder-only models (e.g., OPT and LLaMA), which shows clusters of similar representations across layers (Section. 2).
- We propose CRaSh, a training-free strategy to enhance layer dropping compression (Section. 3). CRaSh improves the performance of fine-tuning without full model and even outperforms knowledge distillation on multiple datasets (Section. 4).
- We analyze the optima of fine-tuning with and without full model through the lens of loss surface and mode connectivity, which shows the two minima fall over the same basin and are connected linearly in parameter space. This observation explains the effectiveness of CRaSh (Section. 5).

2 Empirical Analysis

In this section, we analyze the inherent similarity of layers in LLMs from two complementary perspectives: (i) representation similarity (Section. 2.1), which examines the differences in activations among intermediate layers, and (ii) functional similarity (Section. 2.2), specifically the variations in predictions among intermediate layers.

2.1 Representation Similarity

Given a LLM, which produces word representations (i.e., hidden states) at each layer and aggregates them into sentence representations. We measure the similarity of sentence representations among layers using linear centered kernel alignment (CKA) (Kornblith et al., 2019). CKA emphasizes the distributivity of information. If two layers exhibit similarity across all their neurons, the similarity will be higher, even if individual neurons do not have similar matching pairs or are not well represented by all neurons in the other layer. The representation similarity reveals correlations between layers within LLMs. The inherent similarity in the representation of layers across two

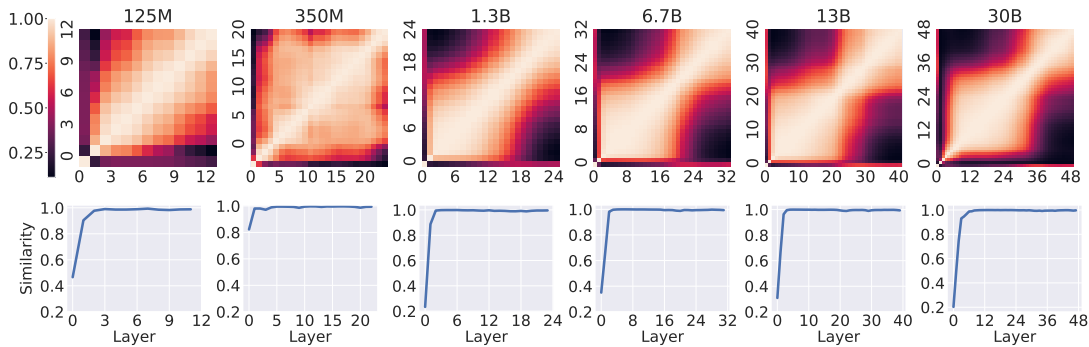


Figure 2: This table presents the representation similarity among all layers (shown above the heatmaps) and the similarity between adjacent layers (represented by the line charts) on the Wikitext corpus (Merity et al., 2017).

datasets are demonstrated in Figure 1 and Figure 2. We provide a detailed explanation of our two main findings as follows:

Finding 1: Emergence of modular structure.

As shown in Figure 1 and Figure 2, we observe that as the number of parameters increases, distinct blocks or modules with high similarity emerge in the representations of different layers. We refer to these blocks of high-similarity representations as *modular structure*. The emergence of *modular structure* can be seen as a self-organizing behavior during the pre-training of LLMs, where the internal representations gradually differentiate into modules with specific functions or semantics. This phenomenon has been briefly examined in previous studies (Phang et al., 2021; Merchant et al., 2020; Chen et al., 2021; Chiang et al., 2020). To the best of our knowledge, no study has investigated this question on LLMs with billions of parameters.

Additionally, our initial findings indicate that there are no evident clusters of layers in pre-trained models with millions of parameters, which may indicate insufficient capacity to comprehend tasks in zero-shot setting. However, when the model size reaches a certain threshold, referred to as *modular point*, *modular structure* emerges in LLMs, resulting in the formation of distinct clusters. Our experiments have shown that the specific *modular point* varies across tasks. Furthermore, we observe that the *modular point* is larger for harder tasks, but smaller for easier tasks, such as language modeling. For example, in the case of the ARC dataset (a question answering task with instruction format), *modular point* is observed to be 10B, as depicted in Figure 1. On the other hand, for the Wikitext corpus (a language modeling task), *modular point* is found to be 1.3B, as illustrated in Figure 2.

Finding 2: Subtle changes in representation

among layers. In addition to *modular structure*, we can also observe high similarity along the diagonal of the similarity matrix. This indicates that intermediate layers may exhibit significant similarity to their adjacent layers. We directly examine the representation similarity between adjacent layers in Figure 2, where point at x_i means similarity between layer i and layer $i + 1$. In addition to the low similarity observed in the bottom layers, starting from about the 5th layer, there is a significantly higher similarity compared to adjacent layers.

Furthermore, we broaden the scope of these findings to include more LLMs and datasets, uncovering a consistent trend of *modular structure* emergence. The details of results, as well as implementation details, are provided in Appendix A.1.

2.2 Functional Similarity

In addition, a complementary perspective to representation similarity involves extracting specific concepts from the hidden states. For example, we can convert the hidden states at each intermediate layer into a probability distribution over the vocabulary (nostalgebraist, 2020; Belrose et al., 2023). This approach facilitates a deeper comprehension of the functional aspects of the layers. For the analysis of functional similarity, we utilize the state-of-the-art tool Tuned-Lens[§] to obtain predictions from the intermediate layers. Additional details are provided in Appendix A.2.

Finding 3: Removing layers within a cluster maximizes behavior invariance. In the sub-figure labeled ①full model of Figure 3, we observe subtle changes as the depth increases and note that adjacent layers display a high similarity in hidden predictions, resulting in the formation of clusters.

[§]<https://github.com/AlignmentResearch/tuned-lens>

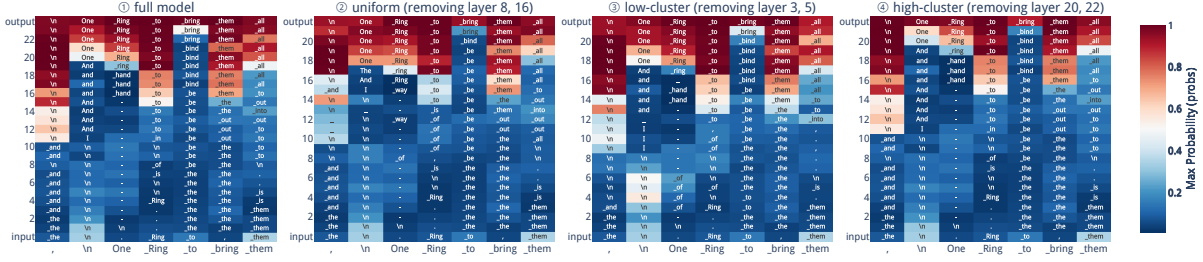


Figure 3: This figure shows results of Tuned-lens on OPT-1.3B and three variants of layer dropping. The entire input text consists of "One Ring to rule them all, \n One Ring to find them, \n One Ring to bring them all \n and in the darkness bind them", where tokens from position 14 to 21 are indicated.

To assess the redundancy of layers, we eliminate multiple layers from the cluster based on representation similarity in Figure 2 and compare the predictions when these layers are uniformly dropped. Based on the results, we also observe all the removal strategies yield predictions that exhibit overall similarity to the internal layers of the full model, showing only minor differences in probability, as indicated by subtle variations in color shades. In comparison to the ①full model, the ②uniform strategy exhibits notable differences in the middle layers of token one, high layers of token four, and the last two tokens, indicating the presence of impure predictions in these positions. Conversely, the ③low-cluster and ④high-cluster strategies display closer alignment with the full model at these locations. This phenomenon leads to the conclusion that adjacent layers with high representation similarity also demonstrate analogous functional similarity. Furthermore, removing layers from these clusters results in maximum behavior invariance compared to uniformly dropping them.

3 Methodology

Empirical analysis of LLMs can inspire fine-tuning approaches, contributing to privacy protection for both centralized LLMs and user data. In this section, we begin by revisiting Offsite-Tuning (OFT), a representative method for fine-tuning LLMs without full model. Subsequently, we introduce our proposed CRaSh method inspired by Section. 2.

3.1 Revisit Offsite-Tuning

In this section, we provide a brief introduction to the settings and evaluation metrics of Offsite-Tuning (OFT) (Xiao et al., 2023). The primary concern of OFT is to maintain the privacy of both the LLM and user data. Specifically, *the data owner is unable to share their labeled training data with the*

LLM owner, and vice versa, the LLM owner cannot share their model with the data owner.

As shown in Figure 4a, OFT involves compressing the LLM into a smaller emulator by layer dropping and fine-tuning it using privacy data (i.e., ③Emulator Fine-tuning). Subsequently, the block weights are transferred and plug-in the LLM for inference (i.e., ④Plug-in). The main objective of OFT is for the plug-in to exceed the performance of both full zero-shot on the LLM and fine-tuning on the emulator ($④ > ①, ③$), thereby ensuring the overall effectiveness of OFT. Additionally, OFT aims to optimize the performance of the plug-in to closely approximate the results achieved by full fine-tuning on the LLM ($④ \approx ②$).

The key to OFT lies in identifying an emulator that closely resembles the original LLM and subsequently performing fine-tuning to replace the LLM. Drawing from our findings on the empirical analysis of LLMs in Section 2, we propose CRaSh, which is designed to optimize layer dropping and yield superior sub-layer emulators from LLMs, as illustrated in the following sections.

3.2 CRaSh

In this section, we provide a detailed description of the three steps of CRaSh, namely Clustering, Removing, and Sharing as presented in Figure 4b. The concept of Clustering and Sharing are supported by *Finding 1*, which suggests that layers within a cluster share similar functions. Additionally, *Finding 2* and *Finding 3* support the idea of removing layers from clusters, as it helps minimize changes in representations and functions.

Clustering Drawing inspiration from the presence of layer clusters in representations and the gradual change in layer behavior in Section. 2, it is observed that adjacent layers within a cluster may have similar functions. These layers can be

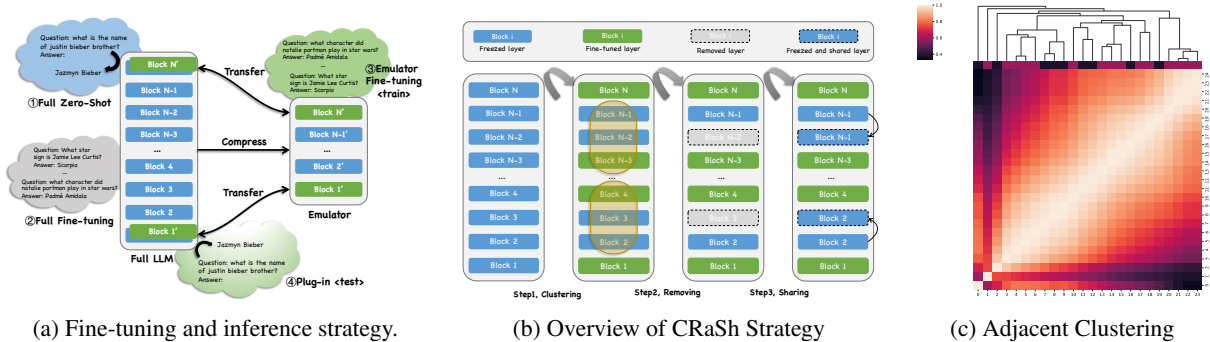


Figure 4: Overview of Offsite-Tuning and CRaSh strategy.

grouped together into a single cluster and subsequently replaced by the cluster center. As shown in Figure 4c, we propose a process for clustering the layers of LLMs based on the similarity of representations between adjacent layers. Initially, each individual layer is considered as a separate cluster. Subsequently, the closest clusters are selected and merged into a new cluster based on the CKA metric of their output representations. This step is repeated until the desired number of clusters is reached. This process bears resemblance to hierarchical clustering (Murtagh and Contreras, 2012), the key distinction lies in the fact that we exclusively cluster the adjacent layers.

Removing Following the clustering of intermediate layers, only layers located at the cluster centers are retained, while the rest within the clusters are removed. Subsequently, a selection of layers is chosen for fine-tuning, where parameters of the bottom and top n layers are learnable in OFT (Xiao et al., 2023) (with $n = 2$). Considering the significance of knowledge contained in the middle layers for downstream tasks, we uniformly select a set of n layers from the remaining layers after removal. The exploration of skill layers (Sajjad et al., 2023; Jordao et al., 2023) based on module cruciality is left as a potential area for future research.

Sharing In the original OFT approach, the model with the remaining layers is considered as an emulator and utilized for fine-tuning on downstream user data. This allows users to experiment with different strategies to optimize the emulator’s performance. For downstream fine-tuning, we propose a straightforward strategy to enhance the performance of emulator. Considering the emergent abilities of LLMs, certain features, such as chain-of-thought (Wei et al., 2022b), may not be present in shallow layer models. Drawing inspiration from the concept of layer sharing (Lan et al., 2020),

we implement layer sharing within the remaining model to achieve optimal results.

4 Experiments

4.1 Setup

Dataset. We evaluate CRaSh on three tasks and eight datasets which are used in Offsite-Tuning (Xiao et al., 2023), including Multi-Choice QA: OpenBookQA (Mihaylov et al., 2018), PIQA (Bisk et al., 2020), SciQ (Welbl et al., 2017), RACE (Lai et al., 2017); Closed-Book QA: ARC-Easy/Challenge (Clark et al., 2018), WebQuestion (Berant et al., 2013); and Sentence Completion: HellaSwag (Zellers et al., 2019). To enhance zero-shot performance, we organize source and target text in instruction format as lm-evaluation-harness (Gao et al., 2021). We utilize it to evaluate our models and report the accuracy on all benchmarks. For clustering step, we utilize data from the same task as support dataset to maintain the privacy of target dataset, including BoolQ (Clark et al., 2019), TriviaQA (Joshi et al., 2017), and CoPA (Wang et al., 2019). We show details about statistic of datasets in Appendix B.1.

Models. We perform empirical analysis on a range of models, including OPT (from 125M to 30B) (Zhang et al., 2022) and LLaMA (from 7B to 30B) (Touvron et al., 2023). Due to limited computational resources, we primarily conduct main experiments on OPT-1.3b, with plans to scale up to OPT-6.7B and LLaMA-7B. As our primary baselines, we consider models from OFT (Xiao et al., 2023), including a knowledge distillation emulator and a uniform 2-8-2 configuration for OPT-1.3b, 2-18-2 for OPT-6.7B and LLaMA-7B. Here, 1-c-r denotes setting the parameters of bottom l and top r layers as learnable, while c layers are uniformly selected from original LLM and kept

Setting	OpenBookQA	ARC-E	ARC-C	WebQs	PIQA	SciQ	RACE	HellaSwag
<i>Full Large Language Model</i>								
Zero-shot (ZS)	23.4%	56.9%	23.5%	4.6%	71.6%	84.4%	34.2%	41.5%
Fine-tuning (FT)	31.4%	61.3%	27.7%	31.2%	75.2%	92.5%	37.0%	42.7%
<i>Knowledge Distillation (Continual Training)</i>								
Emulator ZS	19.4%	53.9%	21.5%	1.3%	68.7%	80.9%	33.0%	35.1%
Emulator FT	24.8%	58.1%	26.1%	24.3%	71.6%	92.2%	38.6%	37.0%
Plug-in (Xiao et al., 2023)	29.0%	59.4%	27.8%	26.2%	74.5%	92.9%	38.9%	43.3%
<i>Uniform Strategy (Training-free)</i>								
Emulator ZS	13.8%	34.9%	19.0%	0.0%	58.4%	49.8%	22.7%	27.0%
Emulator FT	24.6%	50.4%	21.2%	21.8%	69.3%	89.4%	36.5%	32.7%
Plug-in (base)	26.4%	58.3%	23.0%	21.4%	72.7%	90.8%	37.9%	41.2%
<i>with uniform learnable layers</i>								
Emulator FT	24.2%	51.1%	24.1%	23.7%	69.3%	89.3%	36.9%	33.8%
Plug-in	27.6%	58.8%	24.8%	16.4%	72.6%	92.1%	39.7%	41.2%
<i>CRaSh Strategy (Training-free)</i>								
Emulator ZS	14.0%	35.9%	18.5%	4.7%	57.0%	84.3%	34.2%	25.9%
Emulator FT	25.0%	50.0%	21.5%	21.8%	68.9%	88.9%	38.9%	33.6%
Plug-in (our)	30.2% $\uparrow 4.8$	60.0% $\uparrow 1.7$	24.8% $\uparrow 1.8$	23.7% $\uparrow 2.3$	73.2% $\uparrow 0.5$	93.1% $\uparrow 2.3$	39.9% $\uparrow 2.0$	41.9% $\uparrow 0.7$
<i>w/o layer sharing</i>								
Emulator ZS	14.0%	35.9%	18.5%	0.0%	57.0%	43.3%	23.6%	25.9%
Emulator FT	23.8%	50.0%	21.5%	24.3%	68.8%	89.6%	36.2%	31.2%
Plug-in	25.2%	57.7%	24.6%	17.7%	71.7%	92.2%	39.1%	41.3%

Table 1: Results of CRaSh on OPT-1.3B. The values in red font indicate an increase compared to the uniform strategy, highlighting the superiority of CRaSh. Remarkably, CRaSh outperforms the strategy with knowledge distillation (KD) on several datasets. It is worth noting that KD can further enhance the performance of CRaSh.

frozen during fine-tuning. We present implementation details about experiments in Appendix B.2.

4.2 Experimental results

We present the main results in Table 1 and provide an analysis as follows.

OFT and CRaSh does work well. CRaSh satisfies the condition of OFT, where the performance of plug-in is better than the zero-shot performance of full model and the fine-tuning performance of emulator. The results prove that OFT effectively works for fine-tuning without full model and is beneficial for protecting the privacy of LLMs. Additionally, due to over-parameterization of LLMs (Aghajanyan et al., 2021; Ding et al., 2022b), it may not be necessary to optimize all parameters. Therefore, the performance of plug-in can surpass that of directly fine-tuning on LLMs, particularly on datasets like SciQ and RACE.

CRaSh is better than uniformly dropping strategy. Compared to the uniform layer dropping strategy used in OFT (Xiao et al., 2023), CRaSh is an effective method to boost performance that requires low additional cost and is completely training-free, where lifting effects are indicated in red font. Additionally, CRaSh can outperform the knowledge distillation models in OFT settings on several datasets, such as achieving 1.2% improve-

ments on OpenBookQA and 1.0% on RACE. The knowledge distillation method obtains the emulator by continuously pre-training it on the first block of the Pile corpus (Gao et al., 2020), which aims to align the intermediate representation between emulator and full model. Therefore, CRaSh is complementary to knowledge distillation, which can further improve performance by leveraging the improved emulator initialization provided by CRaSh.

CRaSh works better while scaling up model. As depicted in Table 2, CRaSh remains effective even when scaling up the model from 1B to 7B. The benefits and effectiveness of CRaSh are not restricted to specific model sizes, making it a valuable strategy for enhancing OFT outcomes across models of varying scales. Meanwhile, as the depth increases, layers are more prone to redundancy in LLMs. Therefore, by employing a clustering step, CRaSh eliminates redundant network layers and effectively improves the performance of OFT compared to the uniform strategy.

4.3 Ablation study

Impact of clustering and sharing steps. This section discusses the significance of clustering and sharing steps in CRaSh. We compare the results with and without the clustering step, as shown in Table 1. In OFT (Xiao et al., 2023), the top and

Setting	OpenBookQA	ARC-E	ARC-C	WebQs	PIQA	SciQ	RACE	HellaSwag
<i>OPT-6.7B</i>								
Full ZS	27.6%	65.6%	30.6%	8.8%	76.2%	90.1%	38.2%	50.5%
Emulator ZS	21.4%	55.6%	23.9%	1.5%	57.0%	84.1%	31.1%	28.4%
Emulator FT	29.0%	60.1%	31.1%	22.1%	75.6%	88.4%	36.2%	43.4%
Plug-in (Xiao et al., 2023)	33.8%	66.8%	33.9%	23.9%	77.7%	91.9%	44.1%	52.1%
Plug-in (CRaSH)	38.8% $\uparrow 5.0$	70.7% $\uparrow 3.9$	36.3% $\uparrow 2.4$	26.1% $\uparrow 2.2$	78.0% $\uparrow 0.3$	95.3% $\uparrow 4.2$	45.2% $\uparrow 1.1$	53.4% $\uparrow 1.3$
<i>LLaMA-7B</i>								
Full ZS	28.2%	67.3%	38.2%	0.0%	78.3%	89.7%	40.0%	56.4%
Emulator ZS	15.0%	44.3%	23.5%	0.0%	65.7%	57.6%	30.2%	36.2%
Emulator FT	25.4%	60.0%	28.8%	25.7%	73.6%	91.8%	40.8%	45.0%
Plug-in (Uniform)	33.0%	69.6%	39.0%	27.3%	78.8%	93.5%	44.0%	57.4%
Plug-in (CRaSH)	34.6% $\uparrow 1.6$	71.3% $\uparrow 1.7$	41.8% $\uparrow 2.8$	29.8% $\uparrow 2.5$	80.0% $\uparrow 1.2$	95.1% $\uparrow 1.6$	45.6% $\uparrow 1.6$	58.4% $\uparrow 1.0$

Table 2: Results on OPT-6.7B and LLaMA-7B. CRaSH continues to perform effectively as the model size scales up, and even achieves further improvement, benefiting from the emergence of *modular structure*.

Dataset	OpenBookQA	ARC-E	ARC-C	WebQs
The Wikitext	27.8%	58.5%	24.0%	22.0%
Support Task	30.2%	60.0%	24.8%	23.7%
Downstream Task	29.4%	59.6%	25.1%	24.1%

Table 3: The table presents the plug-in results of CRaSH, considering different data types for the clustering step.

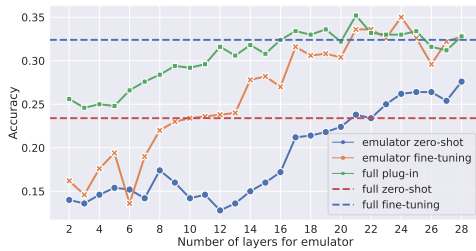


Figure 5: The accuracy varies as the number of layers to be dropped changes on OPT-6.7B model.

bottom two layers are set to be learnable, while the four layers to be updated are uniformly chosen in our CRaSh strategy. Hence, we run the *Uniform Strategy* in "with uniform learnable layers" and compare it with *CRaSh Strategy* without layer sharing (e.g., "w/o layer sharing"). In cases where only the layers of the emulator differ, we find that the clustering step provides slight utility compared to the uniform strategy. This trend may be attributed to the potential loss of hidden information caused by layer dropping. However, this loss can be mitigated by incorporating layer sharing and fine-tuning, resulting in improved performance of the final CRaSh approach. The results in Table 1 also indicate the significance of layer sharing steps, as they enable the emulator to have sufficient depth to handle challenging tasks.

Impact of data type for clustering. In our main experiments, we take into account the privacy of

downstream data. Therefore, we solely utilize data from the support task for clustering, which shares a similar task type with the downstream task. As presented in Table 3, we compare this approach with using public general task and directly downstream dataset in order to examine the impact of data type on clustering and the resulting plug-in performance. By avoiding direct use of the downstream task, which may compromise privacy, we achieve comparable performance by utilizing data solely from a similar support task. We leave it for future work to explore the identification of the most relevant support task for clustering based on downstream task information.

Number of layers for emulator. To ensure a fair comparison, we set the number of layers of emulator to 12 and 22 in main experiments, respectively, for 1B and 7B LLMs. To investigate the impact of an extensive range of layers, we varied the number of clusters from 2 to the maximum number of total layers. The performance of plug-in increases in accordance with the number of layers for the emulator, as depicted in Figure 5. Additionally, we observed that the performance of plug-in can achieve a comparable effect to full fine-tuning when the layers comprise only 50% ~ 60% of the LLMs. However, there is still room for further exploration when transferring fewer layers of LLMs.

5 Discussion

Loss landscape and mode connectivity. In order to comprehend the effectiveness of CRaSh, we conduct an analysis of the relationship between optimal minima derived from plug-in and full model fine-tuning. Firstly, based on Figure 6a, we observe that the initialization resides in a low basin and per-

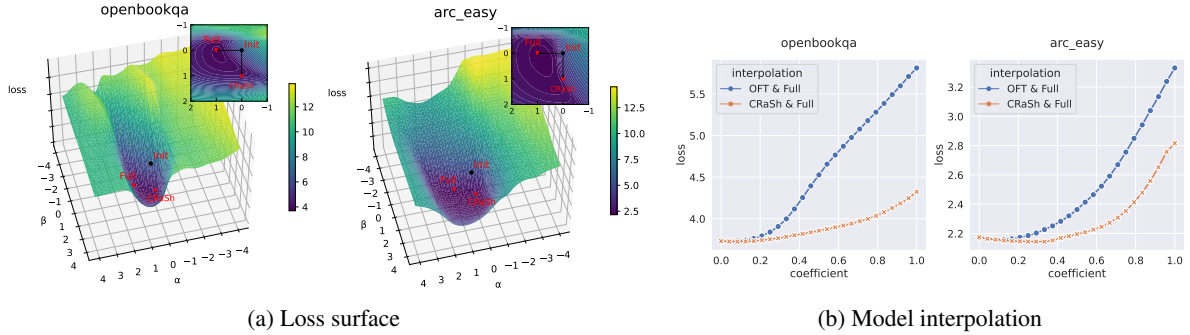


Figure 6: (a) The initialization weights and optima obtained through CRAsh and full model fine-tuning are located within the same basin. (b) Model interpolation on weights from CRAsh, OFT, and full fine-tuning.

forms well across various datasets, which benefits from the over-parameterization and generalization of LLMs. Consequently, by optimizing the LLM at a relatively low cost on the target dataset, it can effectively perform on this dataset. This observation highlights the efficacy of delta-tuning (Ding et al., 2022b) and offsite-tuning. Secondly, the solutions derived from CRAsh and full fine-tuning reside within the same basin. Utilizing the clustering and sharing steps, CRAsh exhibits a closer proximity to full fine-tuning compared to OFT (refer to Figure 6b). Finally, through the interpolation of various solutions, we observe their mode connectivity in the parameter space, wherein CRAsh exhibits a smoother transition towards full fine-tuning compared to OFT, which undergoes more dramatic changes. Based on the visualization of the loss landscape, there is potential to enhance CRAsh for better performance in future directions.

Parameter-Efficient Fine-tuning (PEFT). PEFT has gained popularity as a method for adapting LLMs with minimal parameter updates or additions. For instance, in the case of LoRA, only 590K parameters need to be updated for OPT-1.3B, while OFT requires updating 201M parameters and the full model requires updating 1208M parameters. By applying LoRA to the transferred layers, CRAsh achieves parameter- and resource-efficient fine-tuning. Further details on this topic can be found in Appendix C.2.

Reconstruct full model from emulator. When transmitting the emulator downstream, an important consideration emerges: given the emulators, how challenging would it be to reconstruct the original model? The core question is the attainable performance level with just the emulator. Our findings, detailed in Section 4, discuss the complexities involved in reconstruction: (1) Layer sharing

in CRAsh is viewed as the most effective reconstruction technique. However, it does not replicate the performance of the original model entirely. As indicated in Table 2, the emulator fine-tuned with CRAsh does not achieve the full model’s zero-shot performance. But, when integrated, there’s a marked improvement in performance across multiple datasets, especially ARC-E/C, PIQA, RACE, and HellaSwag. (2) A crucial factor in the reconstruction challenge is the number of transferred layers; fewer transferred layers complicate the reconstruction. Figure 5 demonstrates that accuracy varies with the number of layers omitted. Interestingly, emulators with merely 6 layers (2 frozen and 4 fine-tuned, compared to the 32 layers in the full model) continue to boost the primary LLM’s performance when incorporated. Undoubtedly, CRAsh could be enhanced by incorporating federated learning technologies, including homomorphic encryption (Lee et al., 2022; Chen et al., 2022) and differential privacy (Yue et al., 2021), making the original model’s reconstruction more challenging.

6 Related Work

Delta-tuning (Ding et al., 2022b) methods efficiently update a subset of parameters compared to the entire LLMs (Houlsby et al., 2019; Ben Zaken et al., 2022; Hu et al., 2022; Dettmers et al., 2023). However, these methods require feeding data into the entire LLMs, which is not resource-efficient and raises concerns about the privacy of LLMs. Black-box tuning (Sun et al., 2022b,a), as applied to centralized LLMs, attempts to learn parameters based on input or output text (Cui et al., 2022), which helps protect LLMs but poses risks to user data. Directly manipulating model parameters instead of transferring data has found wide applications in federated learning (McMa-

han et al., 2017), split learning (Vepakomma et al., 2018; Thapa et al., 2022), distributed gradient descent (Huo et al., 2018; Xu et al., 2020; Ni et al., 2023), branch-train-interpolation (Li et al., 2022b; Wortsman et al., 2022), and collaborative machine learning development (Raffel, 2023; Kandpal et al., 2023). These methods either involve model sharing between servers and clients or require multi-turn communication to achieve coverage, which poses limitations when applied to LLMs with billions of parameters. Offsite-Tuning (Xiao et al., 2023) is a notable method that addresses these challenges by selectively sharing layers of LLMs with billions of parameters between servers and clients in a single turn. On the other hand, previous studies have focused on gaining insights into the intermediate representation of neural networks for better fine-tuning (Kornblith et al., 2019; Merchant et al., 2020; Wu et al., 2020; Raghu et al., 2021). In terms of transformers, Phang et al. (2021) observed clustering of layer representations in fine-tuned BERT models (Devlin et al., 2019), supporting the notion of layer redundancy (Dalvi et al., 2020). In contrast, we find that clustering also emerges in pre-trained LLMs as the model size increases, which helps Offsite-Tuning on LLMs. A detailed introduction to related work is presented in Appendix D.

7 Conclusion

In this paper, we uncover block structure of representation within the intermediate layers of LLMs, indicating the clustering of layers in depth models. Based on these observations, we propose a completely training-free strategy to enhance fine-tuning without full model. The strategy consists of three steps: Clustering, Removing, and Sharing (CRaSh). CRaSh boosts the performance of Offsite-Tuning for LLMs on various datasets. Further analysis of the loss surface and mode connectivity provides insights into the effectiveness of CRaSh.

Limitations

This paper primarily focuses on fine-tuning LLMs without using the full model, thereby safeguarding the privacy of both centralized model and data. Our empirical analysis on LLMs has inspired a straightforward yet effective improvement that outperforms previous methods.

However, We have only conducted experiments using two types of LLMs (OPT and LLAMA), leaving a wide range of other LLMs unexplored (such

as Pythia). Due to limited computing resources, our main experiments were conducted on LLMs with a model size of less than 10B.

Although we hypothesize that larger models with redundant layers and CRaSh may lead to improved performance, further exploration is necessary to validate this hypothesis. We utilize representation similarity as a clustering metric, and although it demonstrates satisfactory performance in our experiments, we have encountered challenges and observed instability. Consequently, we intend to investigate functional similarity as an alternative, which may necessitate additional preprocessing time.

Given the complexity involved in validating the plug-in, further research on behavior predicting is required to enhance CRaSh (which tends to be a heuristic strategy) and transform it into an automated learnable strategy (such as reinforcement learning). For future work, we plan to do analysis using more similarity methods and broaden the application of this strategy to encompass a wider range of instructional data and LLMs.

Ethics Statement

Our research on Offsite-Tuning (OFT) and the proposed CRaSh strategy aligns with the ethical guidelines outlined by the ACL Ethics Policy. We recognize the importance of addressing privacy concerns when fine-tuning publicly accessible, centralized Large Language Models (LLMs) with private instruction data.

The primary objective of our work is to enhance the generalization ability of LLMs across various tasks while safeguarding the privacy of both the LLMs and the instruction data. We acknowledge the potential risks associated with the direct transfer of parameterized modules between models and the need for further exploration to fully understand its implications and effectiveness.

Our research adheres to ethical principles by promoting privacy protection, transparency, and responsible use of LLMs. We are committed to continuous ethical evaluation and will contribute to the ongoing discourse on the ethical implications of language model fine-tuning.

Acknowledgements

This work is supported by the National Key R&D Program of China (No. 2022ZD0119101). We extend our gratitude to the anonymous reviewers for their insightful feedback.

References

- Armen Aghajanyan, Sonal Gupta, and Luke Zettlemoyer. 2021. [Intrinsic dimensionality explains the effectiveness of language model fine-tuning](#). In *Proceedings of the 59th Annual Meeting of the Association for Computational Linguistics and the 11th International Joint Conference on Natural Language Processing (Volume 1: Long Papers)*, pages 7319–7328, Online. Association for Computational Linguistics.
- Nora Belrose, Zach Furman, Logan Smith, Danny Halawi, Igor Ostrovsky, Lev McKinney, Stella Biderman, and Jacob Steinhardt. 2023. [Eliciting latent predictions from transformers with the tuned lens](#).
- Elad Ben Zaken, Yoav Goldberg, and Shauli Ravfogel. 2022. [BitFit: Simple parameter-efficient fine-tuning for transformer-based masked language-models](#). In *Proceedings of the 60th Annual Meeting of the Association for Computational Linguistics (Volume 2: Short Papers)*, pages 1–9, Dublin, Ireland. Association for Computational Linguistics.
- Jonathan Berant, Andrew Chou, Roy Frostig, and Percy Liang. 2013. [Semantic parsing on Freebase from question-answer pairs](#). In *Proceedings of the 2013 Conference on Empirical Methods in Natural Language Processing*, pages 1533–1544, Seattle, Washington, USA. Association for Computational Linguistics.
- Steven Bills, Nick Cammarata, Dan Mossing, Henk Tillman, Leo Gao, Gabriel Goh, Ilya Sutskever, Jan Leike, Jeff Wu, and William Saunders. 2023. [Language models can explain neurons in language models](#).
- Yonatan Bisk, Rowan Zellers, Ronan LeBras, Jianfeng Gao, and Yejin Choi. 2020. [PIQA: reasoning about physical commonsense in natural language](#). In *The Thirty-Fourth AAAI Conference on Artificial Intelligence, AAAI 2020, The Thirty-Second Innovative Applications of Artificial Intelligence Conference, IAAI 2020, The Tenth AAAI Symposium on Educational Advances in Artificial Intelligence, EAAI 2020, New York, NY, USA, February 7-12, 2020*, pages 7432–7439. AAAI Press.
- Boli Chen, Yao Fu, Guangwei Xu, Pengjun Xie, Chuanqi Tan, Mosha Chen, and Liping Jing. 2021. [Probing BERT in hyperbolic spaces](#). In *9th International Conference on Learning Representations, ICLR 2021, Virtual Event, Austria, May 3-7, 2021*. OpenReview.net.
- Tianlong Chen, Jonathan Frankle, Shiyu Chang, Sijia Liu, Yang Zhang, Zhangyang Wang, and Michael Carbin. 2020. [The lottery ticket hypothesis for pre-trained BERT networks](#). In *Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020, December 6-12, 2020, virtual*.
- Tianyu Chen, Hangbo Bao, Shaohan Huang, Li Dong, Binxing Jiao, Daxin Jiang, Haoyi Zhou, Jianxin Li, and Furu Wei. 2022. [THE-X: Privacy-preserving transformer inference with homomorphic encryption](#). In *Findings of the Association for Computational Linguistics: ACL 2022*, pages 3510–3520, Dublin, Ireland. Association for Computational Linguistics.
- Xuxi Chen, Tianlong Chen, Weizhu Chen, Ahmed Hassan Awadallah, Zhangyang Wang, and Yu Cheng. 2023. [Dsee: Dually sparsity-embedded efficient tuning of pre-trained language models](#).
- Cheng-Han Chiang, Sung-Feng Huang, and Hung-yi Lee. 2020. [Pretrained language model embryology: The birth of ALBERT](#). In *Proceedings of the 2020 Conference on Empirical Methods in Natural Language Processing (EMNLP)*, pages 6813–6828, Online. Association for Computational Linguistics.
- Wei-Lin Chiang, Zhuohan Li, Zi Lin, Ying Sheng, Zhanghao Wu, Hao Zhang, Lianmin Zheng, Siyuan Zhuang, Yonghao Zhuang, Joseph E. Gonzalez, Ion Stoica, and Eric P. Xing. 2023. [Vicuna: An open-source chatbot impressing gpt-4 with 90%* chatgpt quality](#).
- Aakanksha Chowdhery, Sharan Narang, Jacob Devlin, Maarten Bosma, Gaurav Mishra, Adam Roberts, Paul Barham, Hyung Won Chung, Charles Sutton, Sebastian Gehrmann, et al. 2022. [Palm: Scaling language modeling with pathways](#). *ArXiv preprint, abs/2204.02311*.
- Christopher Clark, Kenton Lee, Ming-Wei Chang, Tom Kwiatkowski, Michael Collins, and Kristina Toutanova. 2019. [BoolQ: Exploring the surprising difficulty of natural yes/no questions](#). In *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*, pages 2924–2936, Minneapolis, Minnesota. Association for Computational Linguistics.
- Peter Clark, Isaac Cowhey, Oren Etzioni, Tushar Khot, Ashish Sabharwal, Carissa Schoenick, and Oyvind Tafjord. 2018. [Think you have solved question answering? try arc, the ai2 reasoning challenge](#). *ArXiv preprint, abs/1803.05457*.
- Adrián Csizsárik, Péter Korösi-Szabó, Ákos K. Matszangosz, Gergely Papp, and Dániel Varga. 2021. [Similarity and matching of neural network representations](#). In *Advances in Neural Information Processing Systems 34: Annual Conference on Neural Information Processing Systems 2021, NeurIPS 2021, December 6-14, 2021, virtual*, pages 5656–5668.
- Ganqu Cui, Wentao Li, Ning Ding, Longtao Huang, Zhiyuan Liu, and Maosong Sun. 2022. [Decoder tuning: Efficient language understanding as decoding](#). *ArXiv preprint, abs/2212.08408*.
- Fahim Dalvi, Hassan Sajjad, Nadir Durrani, and Yonatan Belinkov. 2020. [Analyzing redundancy in pretrained transformer models](#). In *Proceedings of the 2020 Conference on Empirical Methods in Natural*

- Language Processing (EMNLP)*, pages 4908–4926, Online. Association for Computational Linguistics.
- Tim Dettmers, Artidoro Pagnoni, Ari Holtzman, and Luke Zettlemoyer. 2023. [Qlora: Efficient finetuning of quantized llms](#).
- Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. 2019. [BERT: Pre-training of deep bidirectional transformers for language understanding](#). In *Proceedings of the 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies, Volume 1 (Long and Short Papers)*, pages 4171–4186, Minneapolis, Minnesota. Association for Computational Linguistics.
- Ning Ding, Shengding Hu, Weilin Zhao, Yulin Chen, Zhiyuan Liu, Haitao Zheng, and Maosong Sun. 2022a. [OpenPrompt: An open-source framework for prompt-learning](#). In *Proceedings of the 60th Annual Meeting of the Association for Computational Linguistics: System Demonstrations*, pages 105–113, Dublin, Ireland. Association for Computational Linguistics.
- Ning Ding, Yujia Qin, Guang Yang, Fuchao Wei, Zonghan Yang, Yusheng Su, Shengding Hu, Yulin Chen, Chi-Min Chan, Weize Chen, Jing Yi, Weilin Zhao, Xiaozhi Wang, Zhiyuan Liu, Hai-Tao Zheng, Jianfei Chen, Yang Liu, Jie Tang, Juanzi Li, and Maosong Sun. 2022b. [Delta tuning: A comprehensive study of parameter efficient methods for pre-trained language models](#).
- Angela Fan, Edouard Grave, and Armand Joulin. 2020. [Reducing transformer depth on demand with structured dropout](#). In *8th International Conference on Learning Representations, ICLR 2020, Addis Ababa, Ethiopia, April 26-30, 2020*. OpenReview.net.
- Jonathan Frankle and Michael Carbin. 2019. [The lottery ticket hypothesis: Finding sparse, trainable neural networks](#). In *7th International Conference on Learning Representations, ICLR 2019, New Orleans, LA, USA, May 6-9, 2019*. OpenReview.net.
- Jonathan Frankle, Gintare Karolina Dziugaite, Daniel Roy, and Michael Carbin. 2020. [Linear mode connectivity and the lottery ticket hypothesis](#). In *Proceedings of the 37th International Conference on Machine Learning, ICML 2020, 13-18 July 2020, Virtual Event*, volume 119 of *Proceedings of Machine Learning Research*, pages 3259–3269. PMLR.
- Elias Frantar and Dan Alistarh. 2023. [Sparsgpt: Massive language models can be accurately pruned in one-shot](#).
- Elias Frantar, Saleh Ashkboos, Torsten Hoeffler, and Dan Alistarh. 2023. [Gptq: Accurate post-training quantization for generative pre-trained transformers](#).
- Leo Gao, Stella Biderman, Sid Black, Laurence Golding, Travis Hoppe, Charles Foster, Jason Phang, Horace He, Anish Thite, Noa Nabeshima, Shawn Presser, and Connor Leahy. 2020. [The pile: An 800gb dataset of diverse text for language modeling](#).
- Leo Gao, Jonathan Tow, Stella Biderman, Sid Black, Anthony DiPofi, Charles Foster, Laurence Golding, Jeffrey Hsu, Kyle McDonell, Niklas Muennighoff, Jason Phang, Laria Reynolds, Eric Tang, Anish Thite, Ben Wang, Kevin Wang, and Andy Zou. 2021. [A framework for few-shot language model evaluation](#).
- Mitchell Gordon, Kevin Duh, and Nicholas Andrews. 2020. [Compressing BERT: Studying the effects of weight pruning on transfer learning](#). In *Proceedings of the 5th Workshop on Representation Learning for NLP*, pages 143–155, Online. Association for Computational Linguistics.
- Geoffrey Hinton, Oriol Vinyals, and Jeff Dean. 2015. [Distilling the knowledge in a neural network](#).
- Neil Houlsby, Andrei Giurgiu, Stanislaw Jastrzebski, Bruna Morrone, Quentin de Laroussilhe, Andrea Gesmundo, Mona Attariyan, and Sylvain Gelly. 2019. [Parameter-efficient transfer learning for NLP](#). In *Proceedings of the 36th International Conference on Machine Learning, ICML 2019, 9-15 June 2019, Long Beach, California, USA*, volume 97 of *Proceedings of Machine Learning Research*, pages 2790–2799. PMLR.
- Edward J. Hu, Yelong Shen, Phillip Wallis, Zeyuan Allen-Zhu, Yuanzhi Li, Shean Wang, Lu Wang, and Weizhu Chen. 2022. [Lora: Low-rank adaptation of large language models](#). In *The Tenth International Conference on Learning Representations, ICLR 2022, Virtual Event, April 25-29, 2022*. OpenReview.net.
- Zhouyuan Huo, Bin Gu, Qian Yang, and Heng Huang. 2018. [Decoupled parallel backpropagation with convergence guarantee](#). In *Proceedings of the 35th International Conference on Machine Learning, ICML 2018, Stockholmsmässan, Stockholm, Sweden, July 10-15, 2018*, volume 80 of *Proceedings of Machine Learning Research*, pages 2103–2111. PMLR.
- Artur Jordao, George Correa de Araujo, Helena de Almeida Maia, and Helio Pedrini. 2023. [When layers play the lottery, all tickets win at initialization](#).
- Mandar Joshi, Eunsol Choi, Daniel Weld, and Luke Zettlemoyer. 2017. [TriviaQA: A large scale distantly supervised challenge dataset for reading comprehension](#). In *Proceedings of the 55th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 1601–1611, Vancouver, Canada. Association for Computational Linguistics.
- Nikhil Kandpal, Brian Lester, Mohammed Muqeeth, Anisha Mascarenhas, Monty Evans, Vishal Baskaran, Tenghao Huang, Haokun Liu, and Colin Raffel. 2023. [Git-theta: A git extension for collaborative development of machine learning models](#). *ArXiv preprint, abs/2306.04529*.

- Max Klabunde, Tobias Schumacher, Markus Strohmaier, and Florian Lemmerich. 2023. [Similarity of neural network models: A survey of functional and representational measures](#). *ArXiv preprint*, abs/2305.06329.
- Simon Kornblith, Mohammad Norouzi, Honglak Lee, and Geoffrey E. Hinton. 2019. [Similarity of neural network representations revisited](#). In *Proceedings of the 36th International Conference on Machine Learning, ICML 2019, 9-15 June 2019, Long Beach, California, USA*, volume 97 of *Proceedings of Machine Learning Research*, pages 3519–3529. PMLR.
- Guokun Lai, Qizhe Xie, Hanxiao Liu, Yiming Yang, and Eduard Hovy. 2017. [RACE: Large-scale ReAding comprehension dataset from examinations](#). In *Proceedings of the 2017 Conference on Empirical Methods in Natural Language Processing*, pages 785–794, Copenhagen, Denmark. Association for Computational Linguistics.
- Zhenzhong Lan, Mingda Chen, Sebastian Goodman, Kevin Gimpel, Piyush Sharma, and Radu Soricut. 2020. [ALBERT: A lite BERT for self-supervised learning of language representations](#). In *8th International Conference on Learning Representations, ICLR 2020, Addis Ababa, Ethiopia, April 26-30, 2020*. OpenReview.net.
- Garam Lee, Minsoo Kim, Jai Hyun Park, Seungwon Hwang, and Jung Hee Cheon. 2022. [Privacy-preserving text classification on BERT embeddings with homomorphic encryption](#). In *Proceedings of the 2022 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies*, pages 3169–3175, Seattle, United States. Association for Computational Linguistics.
- Bo Li, Peng Qi, Bo Liu, Shuai Di, Jingen Liu, Jiquan Pei, Jinfeng Yi, and Bowen Zhou. 2022a. [Trustworthy ai: From principles to practices](#).
- Hao Li, Zheng Xu, Gavin Taylor, Christoph Studer, and Tom Goldstein. 2018. [Visualizing the loss landscape of neural nets](#). In *Advances in Neural Information Processing Systems 31: Annual Conference on Neural Information Processing Systems 2018, NeurIPS 2018, December 3-8, 2018, Montréal, Canada*, pages 6391–6401.
- Margaret Li, Suchin Gururangan, Tim Dettmers, Mike Lewis, Tim Althoff, Noah A Smith, and Luke Zettlemoyer. 2022b. [Branch-train-merge: Embarrassingly parallel training of expert language models](#). *ArXiv preprint*, abs/2208.03306.
- Bill Yuchen Lin, Chaoyang He, Zihang Ze, Hulin Wang, Yufen Hua, Christophe Dupuy, Rahul Gupta, Mahdi Soltanolkotabi, Xiang Ren, and Salman Avestimehr. 2022. [FedNLP: Benchmarking federated learning methods for natural language processing tasks](#). In *Findings of the Association for Computational Linguistics: NAACL 2022*, pages 157–175, Seattle, United States. Association for Computational Linguistics.
- Yuanxin Liu, Fandong Meng, Zheng Lin, Peng Fu, Yanan Cao, Weiping Wang, and Jie Zhou. 2022. [Learning to win lottery tickets in BERT transfer via task-agnostic mask training](#). In *Proceedings of the 2022 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies*, pages 5840–5857, Seattle, United States. Association for Computational Linguistics.
- Brendan McMahan, Eider Moore, Daniel Ramage, Seth Hampson, and Blaise Agüera y Arcas. 2017. [Communication-efficient learning of deep networks from decentralized data](#). In *Proceedings of the 20th International Conference on Artificial Intelligence and Statistics, AISTATS 2017, 20-22 April 2017, Fort Lauderdale, FL, USA*, volume 54 of *Proceedings of Machine Learning Research*, pages 1273–1282. PMLR.
- Amil Merchant, Elahe Rahimtoroghi, Ellie Pavlick, and Ian Tenney. 2020. [What happens to BERT embeddings during fine-tuning?](#) In *Proceedings of the Third BlackboxNLP Workshop on Analyzing and Interpreting Neural Networks for NLP*, pages 33–44, Online. Association for Computational Linguistics.
- Stephen Merity, Caiming Xiong, James Bradbury, and Richard Socher. 2017. [Pointer sentinel mixture models](#). In *5th International Conference on Learning Representations, ICLR 2017, Toulon, France, April 24-26, 2017, Conference Track Proceedings*. OpenReview.net.
- Jack Merullo, Carsten Eickhoff, and Ellie Pavlick. 2023. [Language models implement simple word2vec-style vector arithmetic](#).
- Todor Mihaylov, Peter Clark, Tushar Khot, and Ashish Sabharwal. 2018. [Can a suit of armor conduct electricity? a new dataset for open book question answering](#). In *Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing*, pages 2381–2391, Brussels, Belgium. Association for Computational Linguistics.
- Tomas Mikolov, Kai Chen, Greg Corrado, and Jeffrey Dean. 2013. [Efficient estimation of word representations in vector space](#). *arXiv preprint arXiv:1301.3781*.
- Niklas Muennighoff. 2022. [Sgpt: Gpt sentence embeddings for semantic search](#).
- Fionn Murtagh and Pedro Contreras. 2012. [Algorithms for hierarchical clustering: an overview](#). *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, 2(1):86–97.
- Thao Nguyen, Maithra Raghu, and Simon Kornblith. 2021. [Do wide and deep networks learn the same things? uncovering how neural network representations vary with width and depth](#). In *9th International Conference on Learning Representations, ICLR 2021, Virtual Event, Austria, May 3-7, 2021*. OpenReview.net.

- Zanlin Ni, Yulin Wang, Jiangwei Yu, Haojun Jiang, Yue Cao, and Gao Huang. 2023. [Deep incubation: Training large models by divide-and-conquering](#).
- nostalgebraist. 2020. [interpreting gpt: the logit lens](#). *LessWrong*.
- OpenAI. 2023. [Gpt-4 technical report](#).
- Jason Phang, Haokun Liu, and Samuel R. Bowman. 2021. [Fine-tuned transformers show clusters of similar representations across layers](#). In *Proceedings of the Fourth BlackboxNLP Workshop on Analyzing and Interpreting Neural Networks for NLP*, pages 529–538, Punta Cana, Dominican Republic. Association for Computational Linguistics.
- Colin Raffel. 2023. Building machine learning models like open source software. *Communications of the ACM*, 66(2):38–40.
- Maithra Raghu, Thomas Unterthiner, Simon Kornblith, Chiyuan Zhang, and Alexey Dosovitskiy. 2021. [Do vision transformers see like convolutional neural networks?](#) In *Advances in Neural Information Processing Systems 34: Annual Conference on Neural Information Processing Systems 2021, NeurIPS 2021, December 6-14, 2021, virtual*, pages 12116–12128.
- Hassan Sajjad, Fahim Dalvi, Nadir Durrani, and Preslav Nakov. 2023. [On the effect of dropping layers of pre-trained transformer models](#). *Computer Speech & Language*, 77:101429.
- Victor Sanh, Albert Webson, Colin Raffel, Stephen H. Bach, Lintang Sutawika, Zaid Alyafeai, Antoine Chaffin, Arnaud Stiegler, Arun Raja, Manan Dey, M Saiful Bari, Canwen Xu, Urmish Thakker, Shanya Sharma Sharma, Eliza Szczechla, Taewoon Kim, Gunjan Chhablani, Nihal V. Nayak, Debajyoti Datta, Jonathan Chang, Mike Tian-Jian Jiang, Han Wang, Matteo Manica, Sheng Shen, Zheng Xin Yong, Harshit Pandey, Rachel Bawden, Thomas Wang, Trishala Neeraj, Jos Rozen, Abheesht Sharma, Andrea Santilli, Thibault Févry, Jason Alan Fries, Ryan Teehan, Teven Le Scao, Stella Biderman, Leo Gao, Thomas Wolf, and Alexander M. Rush. 2022. [Multi-task prompted training enables zero-shot task generalization](#). In *The Tenth International Conference on Learning Representations, ICLR 2022, Virtual Event, April 25-29, 2022*. OpenReview.net.
- Siqi Sun, Yu Cheng, Zhe Gan, and Jingjing Liu. 2019. [Patient knowledge distillation for BERT model compression](#). In *Proceedings of the 2019 Conference on Empirical Methods in Natural Language Processing and the 9th International Joint Conference on Natural Language Processing (EMNLP-IJCNLP)*, pages 4323–4332, Hong Kong, China. Association for Computational Linguistics.
- Tianxiang Sun, Zhengfu He, Hong Qian, Yunhua Zhou, Xuanjing Huang, and Xipeng Qiu. 2022a. [BBTv2: Towards a gradient-free future with large language models](#). In *Proceedings of the 2022 Conference on Empirical Methods in Natural Language Processing*, pages 3916–3930, Abu Dhabi, United Arab Emirates. Association for Computational Linguistics.
- Tianxiang Sun, Yunfan Shao, Hong Qian, Xuanjing Huang, and Xipeng Qiu. 2022b. [Black-box tuning for language-model-as-a-service](#). In *International Conference on Machine Learning, ICML 2022, 17-23 July 2022, Baltimore, Maryland, USA*, volume 162 of *Proceedings of Machine Learning Research*, pages 20841–20855. PMLR.
- Yi-Lin Sung, Jaemin Cho, and Mohit Bansal. 2022. [Lst: Ladder side-tuning for parameter and memory efficient transfer learning](#). *ArXiv preprint*, abs/2206.06522.
- Chaofan Tao, Lu Hou, Wei Zhang, Lifeng Shang, Xin Jiang, Qun Liu, Ping Luo, and Ngai Wong. 2022. [Compression of generative pre-trained language models via quantization](#). In *Proceedings of the 60th Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*, pages 4821–4836, Dublin, Ireland. Association for Computational Linguistics.
- Rohan Taori, Ishaan Gulrajani, Tianyi Zhang, Yann Dubois, Xuechen Li, Carlos Guestrin, Percy Liang, and Tatsunori B. Hashimoto. 2023. [Stanford alpaca: An instruction-following llama model](#). https://github.com/tatsu-lab/stanford_alpaca.
- Chandra Thapa, Mahawaga Arachchige Pathum Chamikara, Seyit Camtepe, and Lichao Sun. 2022. [Splitfed: When federated learning meets split learning](#). In *Thirty-Sixth AAAI Conference on Artificial Intelligence, AAAI 2022, Thirty-Fourth Conference on Innovative Applications of Artificial Intelligence, IAAI 2022, The Twelveth Symposium on Educational Advances in Artificial Intelligence, EAAI 2022 Virtual Event, February 22 - March 1, 2022*, pages 8485–8493. AAAI Press.
- Hugo Touvron, Thibaut Lavril, Gautier Izacard, Xavier Martinet, Marie-Anne Lachaux, Timothée Lacroix, Baptiste Rozière, Naman Goyal, Eric Hambro, Faisal Azhar, et al. 2023. [Llama: Open and efficient foundation language models](#). *ArXiv preprint*, abs/2302.13971.
- Praneeth Vepakomma, Otkrist Gupta, Tristan Swedish, and Ramesh Raskar. 2018. [Split learning for health: Distributed deep learning without sharing raw patient data](#). *ArXiv preprint*, abs/1812.00564.
- Alex Wang, Yada Pruksachatkun, Nikita Nangia, Amanpreet Singh, Julian Michael, Felix Hill, Omer Levy, and Samuel R. Bowman. 2019. [Superglue: A stickier benchmark for general-purpose language understanding systems](#). In *Advances in Neural Information Processing Systems 32: Annual Conference on Neural Information Processing Systems 2019, NeurIPS 2019, December 8-14, 2019, Vancouver, BC, Canada*, pages 3261–3275.

- Xiaozhi Wang, Kaiyue Wen, Zhengyan Zhang, Lei Hou, Zhiyuan Liu, and Juanzi Li. 2022a. [Finding skill neurons in pre-trained transformer-based language models](#). In *Proceedings of the 2022 Conference on Empirical Methods in Natural Language Processing*, pages 11132–11152, Abu Dhabi, United Arab Emirates. Association for Computational Linguistics.
- Yizhong Wang, Yeganeh Kordi, Swaroop Mishra, Alisa Liu, Noah A Smith, Daniel Khashabi, and Hananeh Hajishirzi. 2022b. [Self-instruct: Aligning language model with self generated instructions](#). *ArXiv preprint*, abs/2212.10560.
- Yizhong Wang, Swaroop Mishra, Pegah Alipoormolabashi, Yeganeh Kordi, Amirreza Mirzaei, Atharva Naik, Arjun Ashok, Arut Selvan Dhanasekaran, Anjana Arunkumar, David Stap, Eshaan Pathak, Giannis Karamanolakis, Haizhi Lai, Ishan Purohit, Ishani Mondal, Jacob Anderson, Kirby Kuznia, Krima Doshi, Kuntal Kumar Pal, Maitreya Patel, Mehrad Moradshahi, Mihir Parmar, Mirali Purohit, Neeraj Varshney, Phani Rohitha Kaza, Pulkit Verma, Ravsehaj Singh Puri, Rushang Karia, Savan Doshi, Shailaja Keyur Sampat, Siddhartha Mishra, Sujay Reddy A. Sumanta Patro, Tanay Dixit, and Xudong Shen. 2022c. [Super-NaturalInstructions: Generalization via declarative instructions on 1600+ NLP tasks](#). In *Proceedings of the 2022 Conference on Empirical Methods in Natural Language Processing*, pages 5085–5109, Abu Dhabi, United Arab Emirates. Association for Computational Linguistics.
- Jason Wei, Maarten Bosma, Vincent Y. Zhao, Kelvin Guu, Adams Wei Yu, Brian Lester, Nan Du, Andrew M. Dai, and Quoc V. Le. 2022a. [Finetuned language models are zero-shot learners](#). In *The Tenth International Conference on Learning Representations, ICLR 2022, Virtual Event, April 25-29, 2022*. OpenReview.net.
- Jason Wei, Xuezhi Wang, Dale Schuurmans, Maarten Bosma, Ed Chi, Quoc Le, and Denny Zhou. 2022b. [Chain of thought prompting elicits reasoning in large language models](#). *ArXiv preprint*, abs/2201.11903.
- Johannes Welbl, Nelson F. Liu, and Matt Gardner. 2017. [Crowdsourcing multiple choice science questions](#). In *Proceedings of the 3rd Workshop on Noisy User-generated Text*, pages 94–106, Copenhagen, Denmark. Association for Computational Linguistics.
- Mitchell Wortsman, Suchin Gururangan, Shen Li, Ali Farhadi, Ludwig Schmidt, Michael Rabbat, and Ari S Morcos. 2022. [lo-fi: distributed fine-tuning without communication](#). *ArXiv preprint*, abs/2210.11948.
- John Wu, Yonatan Belinkov, Hassan Sajjad, Nadir Durani, Fahim Dalvi, and James Glass. 2020. [Similarity analysis of contextual word representation models](#). In *Proceedings of the 58th Annual Meeting of the Association for Computational Linguistics*, pages 4638–4655, Online. Association for Computational Linguistics.
- Guangxuan Xiao, Ji Lin, and Song Han. 2023. [Offsite-tuning: Transfer learning without full model](#). *arXiv*.
- An Xu, Zhouyuan Huo, and Heng Huang. 2020. [On the acceleration of deep learning model parallelism with staleness](#). In *2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition, CVPR 2020, Seattle, WA, USA, June 13-19, 2020*, pages 2085–2094. IEEE.
- Xiang Yue, Minxin Du, Tianhao Wang, Yaliang Li, Huan Sun, and Sherman S. M. Chow. 2021. [Differential privacy for text analytics via natural text sanitization](#). In *Findings of the Association for Computational Linguistics: ACL-IJCNLP 2021*, pages 3853–3866, Online. Association for Computational Linguistics.
- Rowan Zellers, Ari Holtzman, Yonatan Bisk, Ali Farhadi, and Yejin Choi. 2019. [HellaSwag: Can a machine really finish your sentence?](#) In *Proceedings of the 57th Annual Meeting of the Association for Computational Linguistics*, pages 4791–4800, Florence, Italy. Association for Computational Linguistics.
- Minjia Zhang and Yuxiong He. 2020. [Accelerating training of transformer-based language models with progressive layer dropping](#). In *Advances in Neural Information Processing Systems 33: Annual Conference on Neural Information Processing Systems 2020, NeurIPS 2020, December 6-12, 2020, virtual*.
- Susan Zhang, Stephen Roller, Naman Goyal, Mikel Artetxe, Moya Chen, Shuohui Chen, Christopher Dewan, Mona Diab, Xian Li, Xi Victoria Lin, Todor Mihaylov, Myle Ott, Sam Shleifer, Kurt Shuster, Daniel Simig, Punit Singh Koura, Anjali Sridhar, Tianlu Wang, and Luke Zettlemoyer. 2022. [Opt: Open pre-trained transformer language models](#).
- Chunting Zhou, Pengfei Liu, Puxin Xu, Srinu Iyer, Jiao Sun, Yuning Mao, Xuezhe Ma, Avia Efrat, Ping Yu, Lili Yu, et al. 2023. [Lima: Less is more for alignment](#). *ArXiv preprint*, abs/2305.11206.

A Empirical Analysis

A.1 Representation Similarity Details

To compute the similarity of representations between pairs of layers within LLMs, we employ the technique known as Centered Kernel Analysis (CKA), as introduced by Kornblith et al. (2019). For every layer within LLMs, the hidden state outputs encompass characteristics derived from the input tokens with the shape of (N, L, H) , denoted as \mathbf{h}_i . Here, N signifies the batch size, L denotes the input length, and H represents the hidden size. After getting features of all input tokens, a pooling strategy is used to get sentence embedding for similarity computing, where max pooling is taken. We evaluate CKA between each pair of layers in the LLM to be compared. For layer i and j , which denoted as \mathbf{s}_i and \mathbf{s}_j , both with the shape of (N, H) , the linear CKA is given by:

$$\text{CKA}(\mathbf{s}_i, \mathbf{s}_j) = \frac{\|\mathbf{s}_i^T \mathbf{s}_j\|_F^2}{\|\mathbf{s}_j^T \mathbf{s}_j\|_F \|\mathbf{s}_i^T \mathbf{s}_i\|_F}$$

where $\|\cdot\|_F$ denotes the Frobenius norm.

In contrast to BERT-style models, which incorporate a CLS token for sentence embedding, GPT-style models focus solely on preceding tokens. Therefore, the last token within GPT models often holds the most significant semantic representation. Nevertheless, according to the findings in the experimental study by Muennighoff (2022), employing the weighted mean pooling strategy, which assigns more importance to later tokens, leads to superior results in sentence-level semantic expression and ensures stability even as the depth of layers increases. Consequently, we adopt the weighted mean pooling strategy to obtain the sentence vector within the hidden layers:

$$R_i = \sum_{k=1}^L w_k \mathbf{h}_k, \quad w_k = \frac{i}{\sum_{k=1}^L k}$$

where \mathbf{h}_k is the k th hidden state and R means the sentence embedding of i th layer.

We organize the source and target text samples into an instruction format, as illustrated in Table 5 and Table 6.

For CKA, representation similarity is computed across all input samples. Due to computational constraints, we use a set of 512 samples for computation, which has been found to be sufficient and stable for analyzing the modular structure.

Additionally, we provide results on more datasets and models in Figure 11, Figure 12, and Figure 15. While we employ weighted mean pooling to obtain sentence representations, we also include results using mean pooling in Figure 13 and Figure 14.

A.2 Functional Similarity Details

Logits-Lens was proposed by (nostalgebraist, 2020) as a method to gain insights into the internal workings of GPT-2, with a specific focus on analyzing the logits, which represent the raw outputs generated by the model before applying the softmax function to obtain probabilities. Logits-Lens aims to examine the logits at various layers of GPT models in order to enhance understanding of prediction process in LLMs. Through the inspection of these logits, researchers and developers can gain valuable insights into decision-making process of LLMs and potentially discover underlying patterns or biases. Due to the instability of Logits-Lens, which fails to function effectively in larger and deeper models, (Belrose et al., 2023) introduces Tuned-Lens, where each layer of the model is trained using an affine transformation on a pre-training corpus.

B Main Experimental Details

B.1 Dataset Details

We present statistical results of both downstream tasks (target tasks) and support tasks in Table 4.

B.2 Implementation Details

For empirical analysis, we randomly select 512 samples from the evaluation set of each dataset for CKA computation. Additionally, we perform the clustering step by considering only layers between the l th bottom layers and the last r th top layers, taking into account the coarse changes among them. However, we ensure that the layers of the emulator remain the same as in Offsite-Tuning. We perform a learning rate tuning process on a grid of values and report the runs with the highest emulator performance, where $\{1e-4, 2e-4, 3e-4, 2e-5, 5e-5, 8e-5\}$ for OPT-1.3B and $\{5e-6, 8e-6, 1e-5, 2e-5, 5e-5\}$ for OPT-6.7B and LLaMA-7B. We also select the best adapter layers in both settings, with and without sharing, indicating that the sharing step is an optional component for local clients. Furthermore, the decision to repeat fine-tuned layers is dependent on the available local resources. The experiments

Task	Multi-Choice QA					Closed-Book QA				SentComp	
Dataset Domain	OpenBookQA Sci.Edu	PIQA Physical	SciQ Sci.Edu	RACE Edu.Exam	BoolQ Gen.	ARC-E Gen.	ARC-C Sci.Edu	WebQs Gen.	TriviaQA Gen.	HellaSwag Gen.	CoPA Gen.
Train.Size	4,957	16,113	11,679	62,445	9,427	2,251	1,119	3,589	87,622	39,905	400
Eval.Size	500	1,838	1,000	3,451	3,270	570	299	189	11,313	10,042	100
Test.Size	500	3,084	1,000	3,498	3,245	2,376	1,172	2,032	10,832	10,003	500
Avg.Context	13.10	14.36	110.27	407.90	143.96	28.02	31.15	15.54	24.23	49.18	8.68
Avg.Target	4.87	24.28	3.68	8.68	2.0	5.93	7.28	4.24	4.48	29.52	7.34
Avg.Total	17.97	38.64	113.95	416.58	145.96	33.95	38.43	19.78	28.71	78.69	16.03

Table 4: Statistics are collected for all datasets, with the last one of each task serving as a support task for clustering (e.g., BoolQ, TriviaQA, and CoPA). Abbreviations: SentComp = Sentence Completion, Sci.Edu = Science Education, Edu.Exam = Education and Examination, Gen. = General domains.

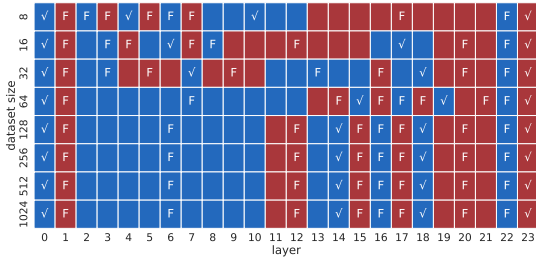


Figure 7: This figure presents clustering results on OPT-1.3B with the Wikitext Corpus, showcasing the influence of varying example numbers (8 to 1024). Adjacent layers within the same cluster are color-coded (red or blue). Emulator layers are marked with F and \checkmark , where the latter indicates learnable.

are conducted using the NVIDIA RTX 3090 GPUs for OPT-1.3B and A6000 GPUs for OPT-6.7B and LLaMA-7B.

C Additional Experiments and Analysis

C.1 Impact of data size for clustering

As illustrated in Section. 3.2, the CKA metric used in clustering step is computed based on the similarity of representation in intermediate layers.

According to previous studies (Wu et al., 2020; Csiszárík et al., 2021; Phang et al., 2021), increasing the amount of data used results in higher accuracy for the CKA metric. However, due to limited computing resources, it is challenging to load all examples into memory once for computation. To reduce memory consumption during computation, Nguyen et al. (2021) proposed computing linear CKA by averaging HSIC scores based on mini-batches. However, being limited with computing resource, it’s hard to feed all examples into memory for computing. In contrast to their approach, we focus on the clustering process itself and analyze the results using varying sizes of examples, as shown in Figure 7. Our findings indicate that the

clustering results tend to stabilize as the data size increases up to 128. Based on these findings, downstream users can now upload only a small amount of data relevant to their task, resulting in improved clustering.

C.2 Combined with parameter-efficient tuning

OFT is independent of parameter-efficient tuning methods, including Adapter (Houlsby et al., 2019), BitFit (Ben Zaken et al., 2022), and LoRA (Hu et al., 2022). For example, in the case of LoRA, only 590K parameters need to be updated for OPT-1.3B, compared to 201M for OFT and 1208M for the full model. This demonstrates the parameter- and resource-efficiency achieved through OFT. Based on results presented in Figure 8, we observe that CRaSh is also compatible with LoRA and exhibits superior performance. Nevertheless, there is still a noticeable performance decline on various datasets that requires further exploration in future studies.

C.3 Sharing among different layers

Layer sharing is a beneficial approach to enhance model capacity when faced with limited resources (Lan et al., 2020). The downstream user has the option to either share weights among layers or not, depending on the emulator’s performance. In order to investigate the impact of weight sharing across different layers, we substitute each layer in LLMs with another layer. As illustrated in Figure 9, the heatmap above displays the loss on the validation dataset when replacing layer i with layer j . The diagonal represents the original LLMs, where the loss is the lowest, and locations near the diagonal also exhibit low loss. Additionally, in the heatmap below, we compare the representations from the last layer of the original LLM and the layer sharing models, which demonstrates a similar

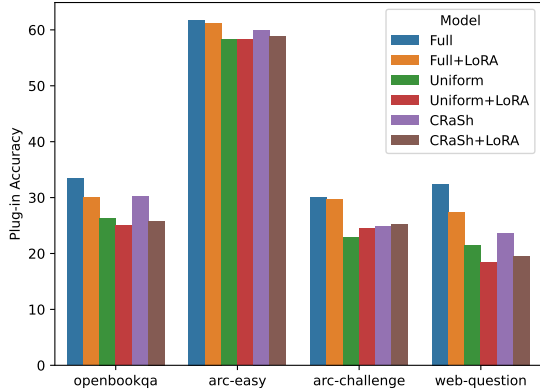


Figure 8: The table presents the plug-in accuracy for four datasets when combining LoRA with different strategies. It is evident that CRaSh performs well with LoRA compared to the uniform strategy. Although LoRA significantly reduces the number of learnable parameters by optimizing the model in a low-rank space, it negatively impacts performance in almost all datasets.

phenomenon. These analyses collectively indicate that weights sharing between adjacent layers can maintain comparable performance to the primary model. This finding supports the effectiveness of the layer sharing steps in CRaSh.

C.4 Comparing layer clustering to module cruciality

As demonstrated in Figure 10, we showcase module cruciality through the process of rewinding and removing layers. The findings reveal that the majority of important neurons are concentrated in the middle and high layers of the model. This supports our decision to uniformly select learnable layers. However, further investigation is required for a more comprehensive understanding of this phenomenon.

D Related Works

In this section, we first review the adaptation methods for LLMs, then introduce a technique called fine-tuning without full models. After that, we discuss the compression methods for LLMs. Finally, we present similarity methods for interpreting LLMs to enhance adaptation.

Parameter- and resource-efficient fine-tuning has emerged as a popular method for adapting LLMs. Instead of directly updating pre-trained models for downstream tasks, these methods focus on updating or adding a minimal number of parameters, sometimes not requiring the involvement of the entire parameter set. Regarding parameter-

efficient fine-tuning, Houlsby et al. (2019) introduced task-specific modules called adapters, such as bottleneck networks, into LLMs. Taking into account the intrinsic space of LLMs (Aghajanyan et al., 2021), LoRA (Hu et al., 2022) optimizes LLMs in a low-rank space, where additional matrices are updated and can be directly added to the original parameter matrix. Except for inserting new parameters, two other approaches, BitFit (Ben Zaken et al., 2022) and skill neurons (Wang et al., 2022a), aim to identify task-related parameters within LLMs and update them to incorporate task-specific knowledge while keeping the remaining model parameters frozen. Another approach is black-box tuning (BBT) (Sun et al., 2022b,a), which involves LLMs that are inaccessible to users. In this method, the continuous prompt prepended to the input text is optimized using derivative-free optimization techniques. However, in these methods, the full models are required to participate in forward propagation, and they do not provide any assistance in protecting the privacy of LLMs and data. Another approach is resource-efficient fine-tuning, which involves evolving only a subset of parameters during the fine-tuning process (Sung et al., 2022; Chen et al., 2023). These methods solely focus on transferring knowledge in one direction to downstream tasks and do not facilitate the transfer of updated weights back to the original model.

Fine-tuning without using full models is motivated by the need for privacy protection, which is not adequately addressed by current transfer learning methods. Federated learning (FL) (McMahan et al., 2017) involves distinguishing server and client models, where training is performed locally on the client and then aggregated. However, the client and server retain the same model, which compromises the privacy of LLMs. Another approach is decoupled learning, which decomposes the end-to-end optimization problem of neural training into smaller subproblems. This objective is achieved through various techniques, such as distributed gradient descent (Huo et al., 2018; Xu et al., 2020), model assembly (Ni et al., 2023), branch-train-interpolation (Li et al., 2022b; Wortsman et al., 2022), and collaborative development of machine learning (Raffel, 2023; Kandpal et al., 2023). However, these methods primarily focus on training from the beginning rather than during the fine-tuning phase or risk leaking the full model. To ad-

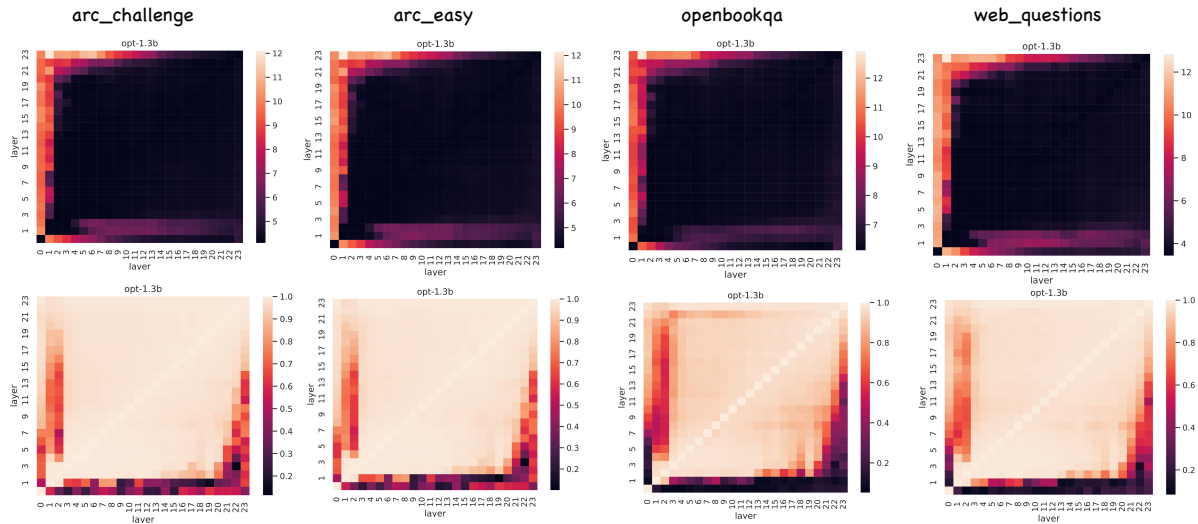


Figure 9: Analysis on layer sharing. (i, j) means replacing layer i with layer j , i.e. sharing layer j with layer i . Above: loss on validation set. Below: representation similarity compared to last layer.

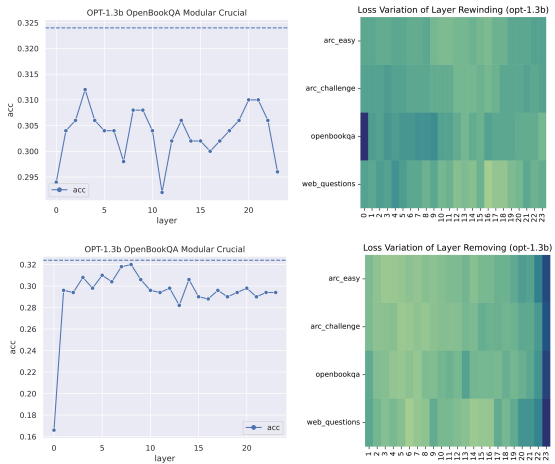


Figure 10: Given a full finetuned model, we evaluate specific layer importance via rewinding weights of layer to initialization (above) and directly removing layer from finetuned model (below).

address this issue, Xiao et al. (2023) propose Offsite-Tuning, a novel approach that involves transferring compressed versions of LLMs to downstream tasks and performing fine-tuning on privacy-sensitive user data. The updated weights are then transferred back and incorporated into LLMs. This method shows promise for protecting the privacy of LLMs and user data. This work is highly relevant to our research, and we propose a training-free strategy to enhance offsite-tuning by leveraging the similarities among neural networks.

Compression methods for LLMs To address resource-constrained scenarios, various technologies such as knowledge distillation (Hinton et al., 2015; Sun et al., 2019; Gordon et al., 2020), pruning (Chen et al., 2020; Liu et al., 2022), and quantization (Tao et al., 2022) have been employed in pre-trained models such as BERT, T5, and GPT-2. However, with the increasing size of LLMs, such as GPT-3 which consists of 96 layers, knowledge distillation becomes challenging. With the increasing popularity of post-quantization, methods such as GPTQ (Frantar et al., 2023) and QLoRA (Dettmers et al., 2023) have emerged to reduce the computational resources required by LLMs. However, these methods still encounter challenges related to loss of precision and model leakage, posing threats to the privacy and safety of LLMs. SparseGPT (Frantar and Alistarh, 2023) demonstrated, for the first time, the possibility of pruning large-scale generative pretrained transformer (GPT) family models to achieve at least 50% sparsity in a single opera-

tion. In comparison to the aforementioned methods, LayerDrop is an effective technique for reducing the parameters of LLMs while maintaining comparable performance. [Fan et al. \(2020\)](#) explored the use of LayerDrop to reduce the depth of transformers, but this approach relies on a specialized training strategy. Building on this, [Zhang and He \(2020\)](#) proposed the concept of layer drop to expedite training. These studies primarily focus on training with layer drop during the training process rather than during post-training. [Sajjad et al. \(2023\)](#) investigated various strategies for implementing layer drop on pre-trained models such as BERT, XLNet, and GPT-2, with a particular emphasis on the application of heuristic rules. Building upon the concept of "lottery tickets" ([Frankle and Carbin, 2019](#)), which involves discovering sparse subnetworks within trained dense networks that can achieve comparable accuracy, [Jordao et al. \(2023\)](#) confirmed the presence of winning tickets when layers are pruned in vision models. Insufficient exploration has been conducted on the application of layer dropping in large-depth neural networks such as LLMs.

Neural network similarity primarily encompasses representation similarity and functional similarity. Representation similarity refers to the similarity of hidden states across all layers, while functional similarity indicates that two models exhibit the same behavior on the given inputs ([Klabunde et al., 2023](#)). By measuring the similarity of neural network representations, we can gain insights into the reasons behind variations in model behavior. [Kornblith et al. \(2019\)](#) revisited previous methods for comparing neural network representations and introduced centered kernel alignment (CKA), a technique that measures the relationship between representations without being affected by high dimensionality or the number of data points. Extensive exploration has been conducted in the field of computer vision. In comparison to CNN models, [Raghu et al. \(2021\)](#) discovered significant differences in the representation structure between Vision Transformers (ViTs) and convolutional networks. ViTs exhibit highly similar representations across all layers, whereas ResNet models demonstrate lower similarity between lower and higher layers, indicating the absence of a block structure in the representation of transformer models. In the study of large language models, researchers have analyzed representation similarity across different

pre-trained models, comparing them within various model families ([Wu et al., 2020](#)), and have investigated the dynamics of embeddings during fine-tuning ([Merchant et al., 2020](#)). [Phang et al. \(2021\)](#) discovered the clustering of layer representations in fine-tuned transformers, providing evidence for the presence of layer redundancy in LLMs ([Dalvi et al., 2020](#)). As the size increases, we observe that clustering also occurs in original pre-trained models, not just in specialized models. Recognizing the wide applicability of this concept in various fields, recent studies have aimed to gain insights into the functional aspects of LLMs. [nostalgebraist \(2020\)](#) directly mapped the hidden states of intermediate layers to the final classification layer to obtain hidden predictions. Considering the phenomenon of representation drift within hidden layers, especially in lower layers, [Belrose et al. \(2023\)](#) propose tuned-lens, a method that trains projections for each layer using a small amount of pre-trained corpus. These methods indicate that the functional behaviors of hidden layers also undergo subtle changes as the depth of the layers increases. Building upon these observations, [Merullo et al. \(2023\)](#) discovered that language models implement simple word2vec-style vector arithmetic ([Mikolov et al., 2013](#)), which sheds light on the prediction process of LLMs. Instead of using the transformation layer for decoding, [Bills et al. \(2023\)](#) attempted to interpret GPT-2 hidden states using GPT-4 ([OpenAI, 2023](#)), opening up the possibility of automatically aligning the behavior of models with AI.

OpenBookQA

Which organism cannot specialize?
protozoa

A person can grow cabbage in January with the help of what product?
Green house

PIQA

Question: To fight Ivan Drago in Rocky for sega master system.

Answer:

You have to defeat Apollo Creed and Clubber Lang first.

Question: Make outdoor pillow.

Answer:

Blow into trash bag and tie with rubber band.

SciQ

A wetland is an area that is wet for all or part of the year. Wetlands are home to certain types of plants. Question: What is an area of land called that is wet for all or part of the year?

Answer:

wetland

Question: Surface waters are heated by the radiation from?

Answer:

the sun

RACE

Article: I am a psychologist. I first met Timothy, a quiet, overweight eleven-year-old boy, when his mother brought him to me to discuss his declining grades. A few minutes with Timothy were enough to confirm that his self-esteem and general happiness were falling right along with _ . I asked about Timothy's typical day. He awoke every morning at six thirty so he could reach his school by eight and arrived home around four thirty each afternoon. He then had a quick snack, followed by either a piano lesson or a lesson with his math tutor. He finished dinner at 7 pm, and then he sat down to do homework for two to three hours. Quickly doing the math in my head, I found that Timothy spent an average of thirteen hours a day at a writing desk.

What if Timothy spent thirteen hours a day at a sewing machine instead of a desk? We would immediately be shocked, because that would be called children being horribly mistreated. Timothy was far from being mistreated, but the mountain of homework he faced daily resulted in a similar consequence –he was being robbed of his childhood. In fact, Timothy had no time to do anything he truly enjoyed, such as playing video games, watching movies, or playing board games with his friends. Play, however, is a crucial part of healthy child development. It affects children's creativity, their social skills, and even their brain development. The absence of play, physical exercise, and freefrom social interaction takes a serious toll on many children. It can also cause significant health problems like childhood obesity, sleep problems and depression.

Experts in the field recommend the minutes children spend on their homework should be no more than ten times the number of their grade level. As a fifthgrader, Timothy should have no more than fifty minutes a day of homework (instead of three times that amount). Having an extra two hours an evening to play, relax, or see a friend would soundly benefit any child's life quality.

Question: According to the passage, how long should a thirdgrader spend a day doing homework?

Answer:

No more than thirty minutes.

BoolQ <support set>

Phantom pain – Phantom pain sensations are described as perceptions that an individual experiences relating to a limb or an organ that is not physically part of the body. Limb loss is a result of either removal by amputation or congenital limb deficiency. However, phantom limb sensations can also occur following nerve avulsion or spinal cord injury.

Question: is pain experienced in a missing body part or paralyzed area?

Answer:

yes

Table 5: Instructions format of Multi-Choice QA task.

<i>ARC-E</i>
Question: Which technology was developed most recently? Answer: <i>cellular telephone</i>
Question: A student hypothesizes that algae are producers. Which question will best help the student determine if this is correct? Answer: <i>Do algae use sunlight to make food?</i>
<i>ARC-C</i>
Question: Juan and LaKeisha roll a few objects down a ramp. They want to see which object rolls the farthest. What should they do so they can repeat their investigation? Answer: <i>Record the details of the investigation.</i>
Question: High-pressure systems stop air from rising into the colder regions of the atmosphere where water can condense. What will most likely result if a high-pressure system remains in an area for a long period of time? Answer: <i>drought</i>
<i>WebQS</i>
Question: what is the name of justin bieber brother? Answer: <i>Jazmyn Bieber</i>
Question: what character did natalie portman play in star wars? Answer: <i>Padmé Amidala</i>
<i>TriviaQA <support set></i>
Question: What star sign is Jamie Lee Curtis? Answer: <i>Scorpio</i>
Question: Which Lloyd Webber musical premiered in the US on 10th December 1993? Answer: <i>Sunset Boulevard</i>
<i>HellaSwag</i>
Roof shingle removal: A man is sitting on a roof. He <i>starts pulling up roofing on a roof.</i>
Clean and jerk: A lady walks to a barbell. She bends down and grabs the pole. The lady <i>stands and lifts the weight over her head.</i>
<i>CoPA <support set></i>
The man turned on the faucet therefore <i>water flowed from the spout.</i>
The girl found a bug in her cereal therefore <i>she lost her appetite.</i>

Table 6: Instructions format of Closed-Book QA and Sentence Completion task.

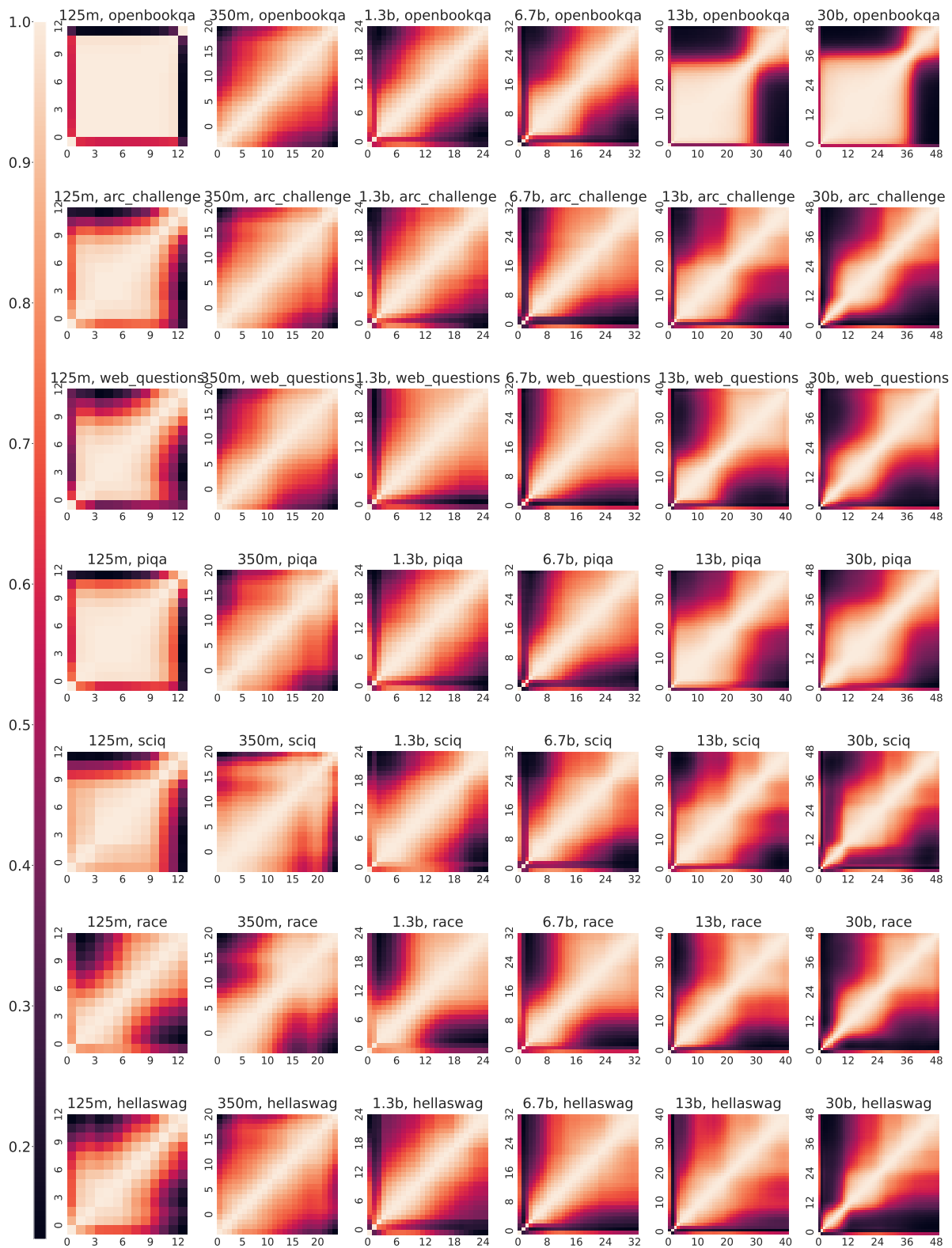


Figure 11: The table displays the representation similarity among layers of OPT models (Zhang et al., 2022) with different sizes, across five datasets with weighted mean pooling strategy. The rows in the table represent the layer similarity of each dataset across the 125M, 1.3B, 6.7B, and 13B OPT models. Notably, the characteristics of the Wikitext dataset differ from the rest because it is a language modeling task similar to the pre-training objective. (Phang et al., 2021) introduced that fine-tuned transformers exhibit clusters of similar representations across layers, which explains the emerging block structure of the Wikitext dataset even in small language models. In contrast, the remaining four datasets are associated with question answering tasks, which pose challenges for smaller models. Consequently, the representation of these tasks demonstrates abnormal similarity in the intermediate layers of the 125M OPT model, suggesting a relatively lower level of comprehension in it.

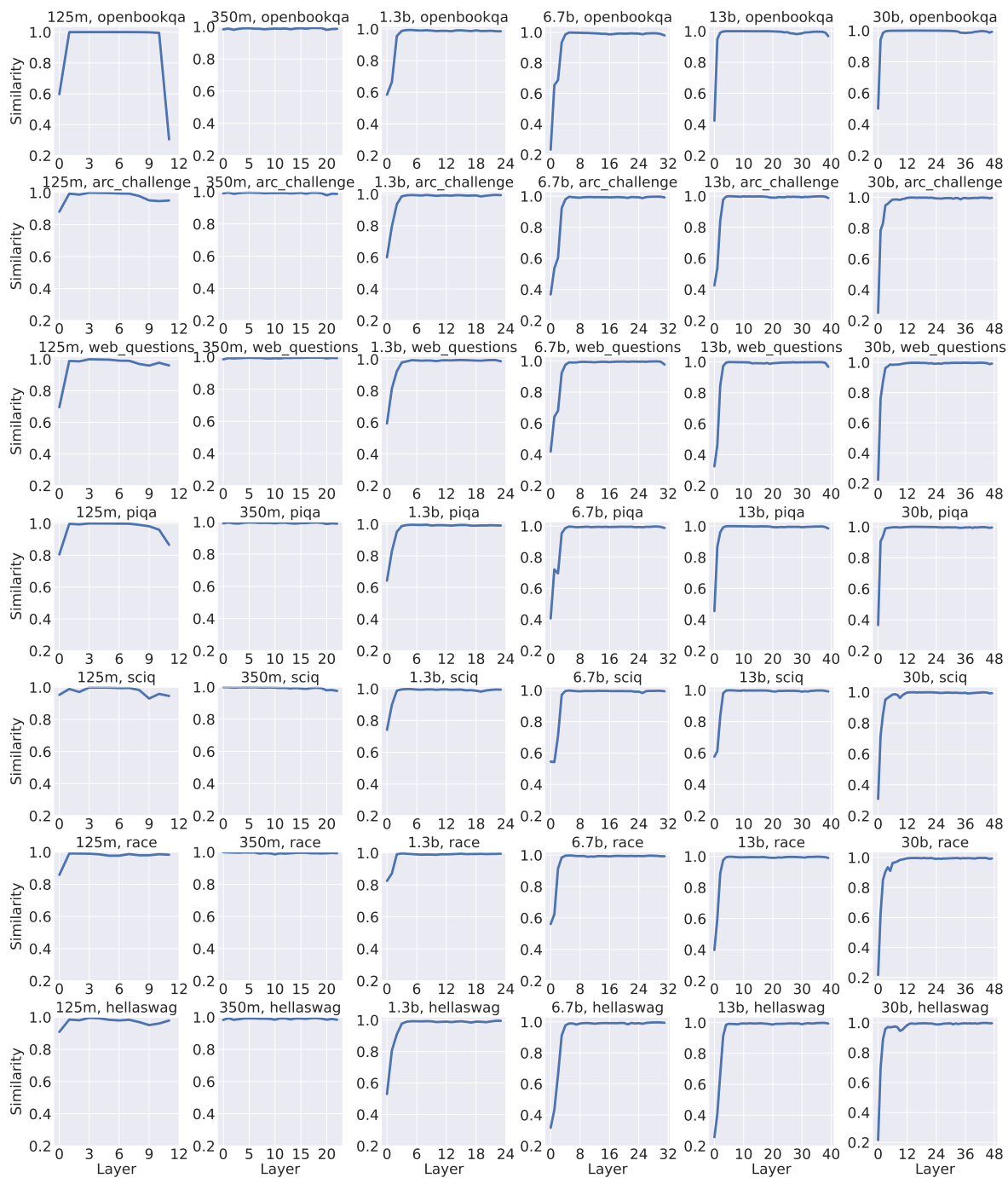


Figure 12: The table displays the representation similarity among layers of OPT models (Zhang et al., 2022) with different sizes, across five datasets with weighted mean pooling strategy.

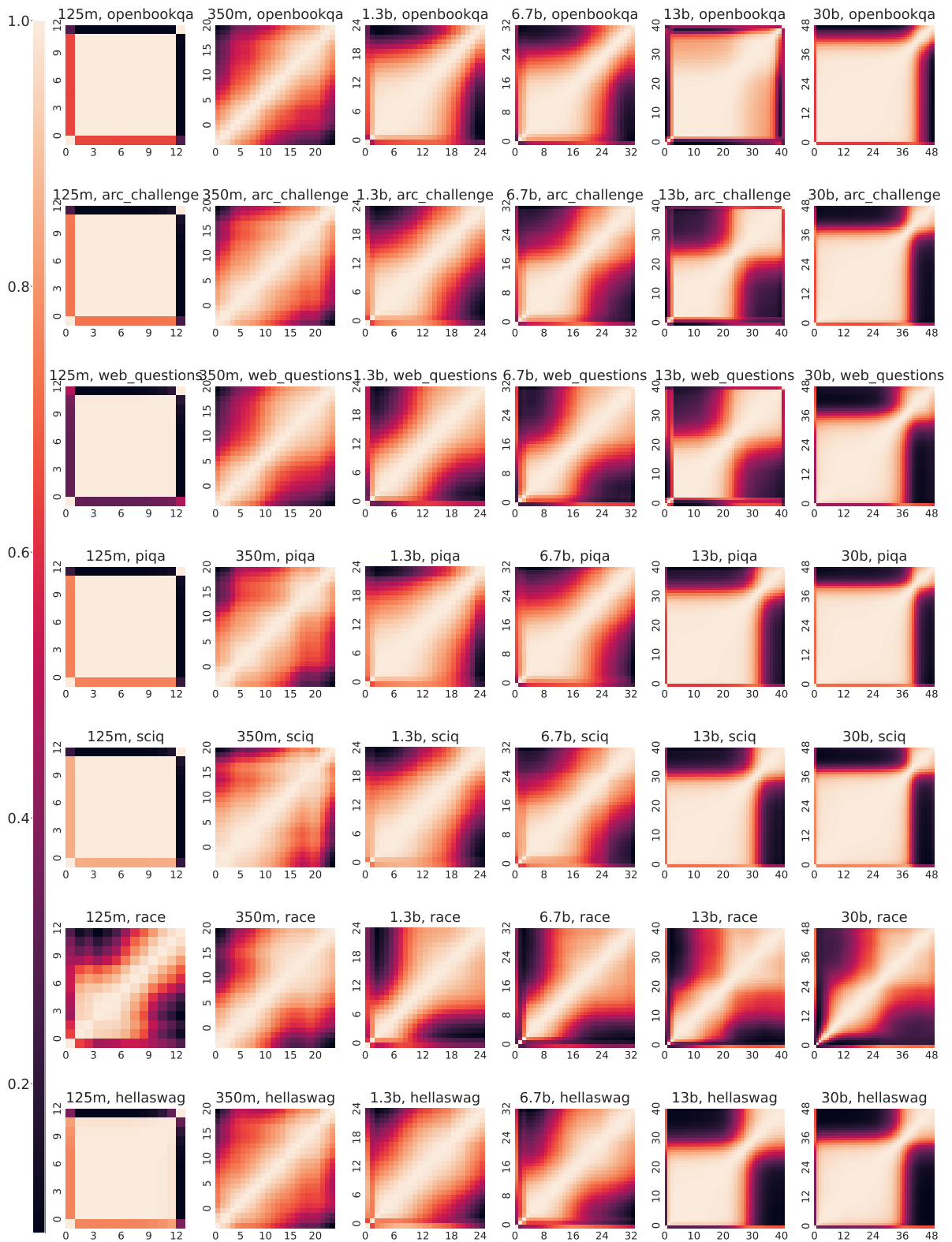


Figure 13: The table displays the representation similarity among layers of OPT models (Zhang et al., 2022) with different sizes, across five datasets with simple mean pooling strategy.

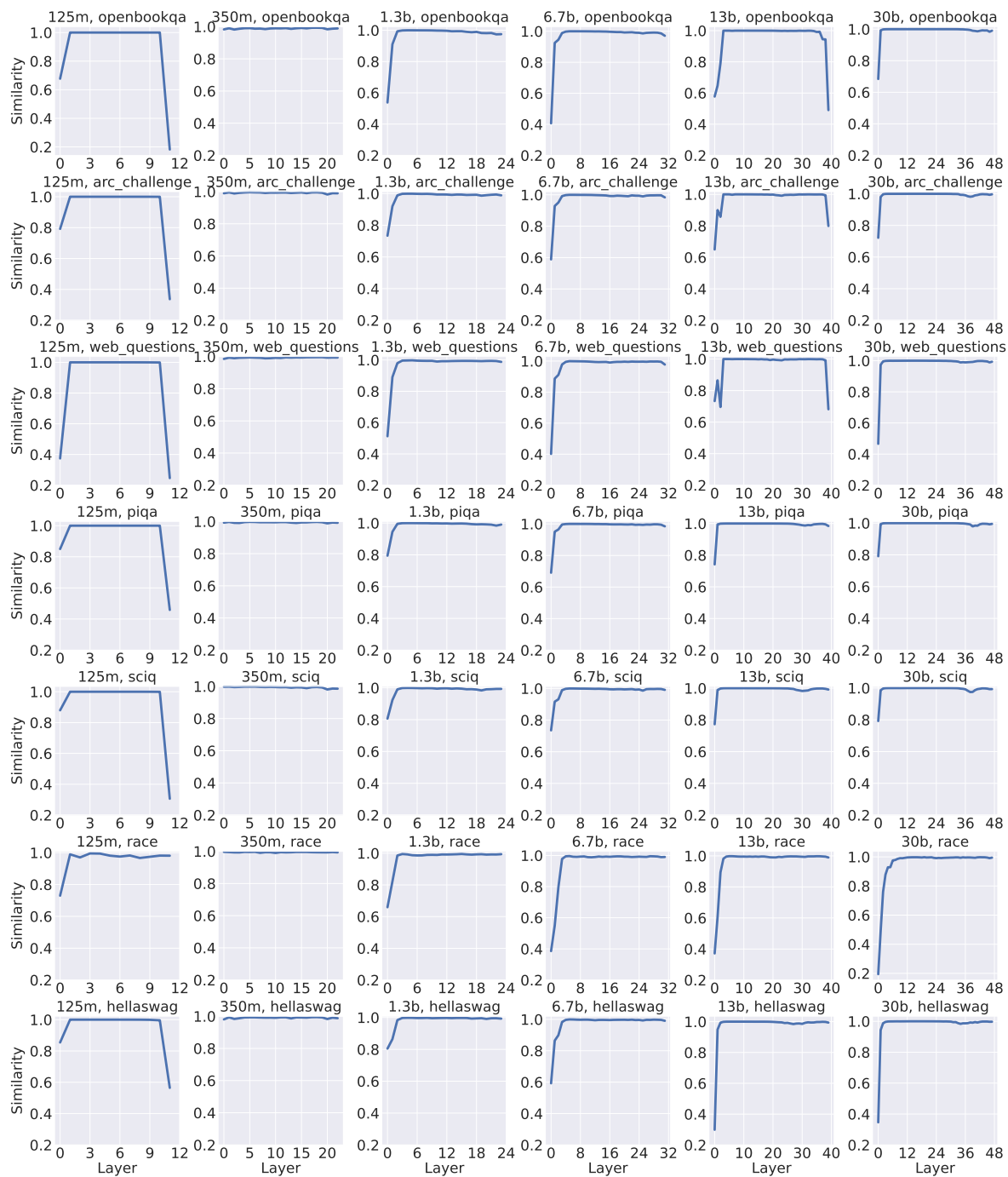
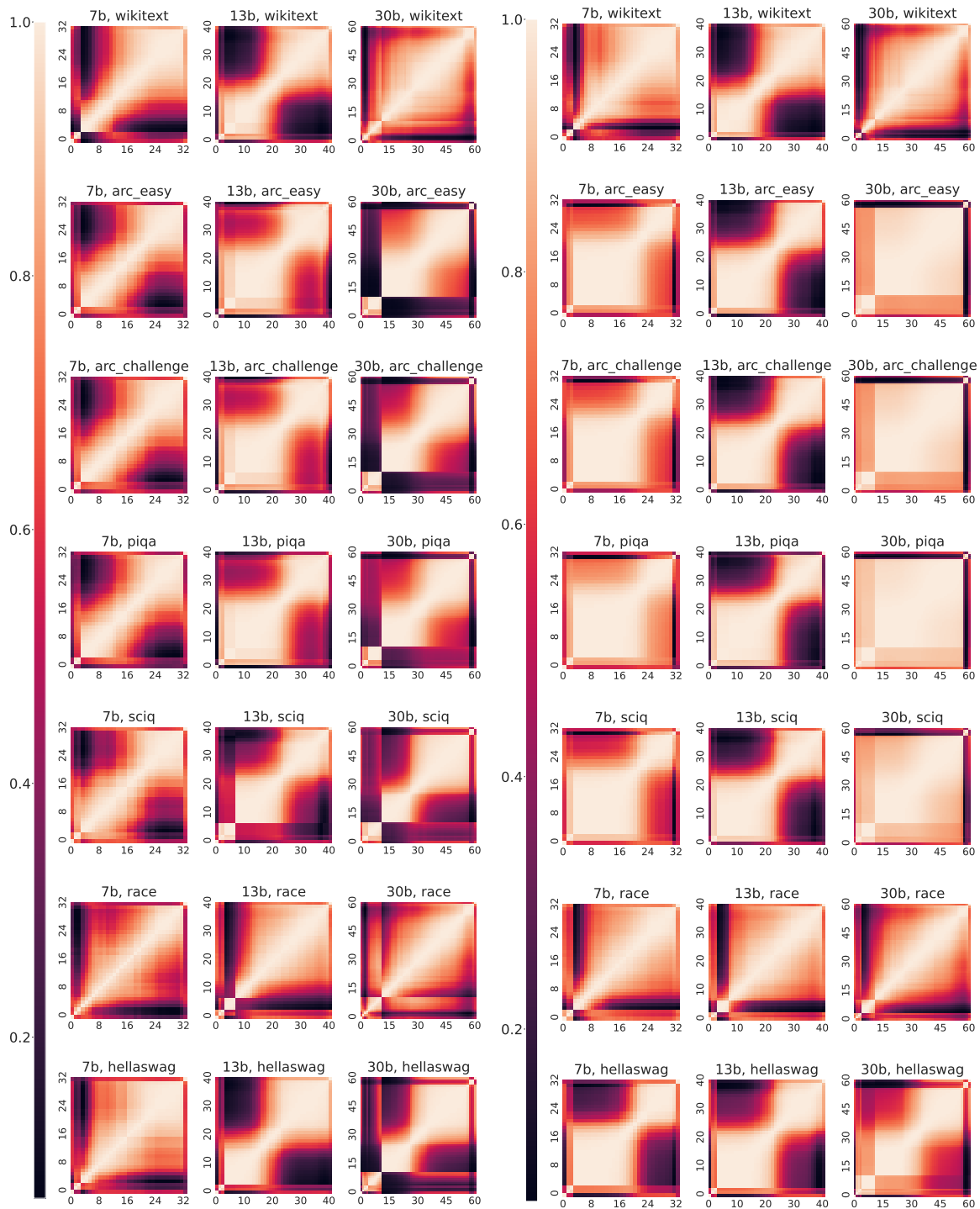


Figure 14: The table displays the representation similarity among layers of OPT models (Zhang et al., 2022) with different sizes, across five datasets with simple mean pooling strategy.



(a) Weighted mean pooling on LLAMA.

(b) Mean pooling on LLAMA.

Figure 15: This table illustrates the presence of a *modular structure* in LLAMA models. We observe that weighted mean pooling performs well on LLAMA models, while direct mean pooling may lead to information loss and abnormal structures, particularly in the case of 30B models.