WHAT MATTERS IN THE STRUCTURED PRUNING OF GENERATIVE LANGUAGE MODELS?

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ABSTRACT

Auto-regressive large language models such as GPT-3 require enormous computational resources to use, leading to huge financial cost and environmental impact. Structured pruning methods traditionally reduce resource usage, however, their application to and efficacy for generative language models is heavily under-explored. We analyze the effects of magnitude, random, and movement (Lagunas et al., 2021) pruning on MLP layers in GPT-like models. We find that movement can underperform for these models while random pruning nearly matches the best methods. By examining neuron-level redundancy measures, we discover that movement does not select neurons based on how *unique* they are compared to other neurons, leaving behind excess redundancy. In view of this, we introduce **G**lobally **U**nique **M**ovement (GUM) to select neurons based on both uniqueness and sensitivity. We then discuss the roles of our techniques on different redundancy metrics through careful comparisons and ablations.

1 INTRODUCTION

Large language models (LLMs), such as the state-of-the-art GPT-3 model (Brown et al., 2020) with up to 175 billion parameters, have achieved remarkable performance in natural language processing (NLP) tasks. However, training and deploying such massive models also poses significant challenges in terms of computational cost, energy consumption, and environmental impact. Therefore, it is crucial to develop effective methods to reduce the size of LLMs without compromising their quality.

Neural network pruning is a long-standing model compression method (Janowsky, 1989; Mozer & Smolensky, 1988; Frankle & Carbin, 2018; Karnin, 1990; Blalock et al., 2020). It can be broadly classified into two types: *unstructured* and *structured*. Unstructured pruning removes individual weights from the network based on some criteria, such as magnitude or movement, resulting in sparse weight matrices that can be stored and processed more efficiently. Structured pruning, on the other hand, eliminates whole components, such as neurons, channels, or blocks, leading to smaller architectures to reduce end-to-end inference latency. While unstructured pruning has been extensively studied and applied to LLMs (Wang et al., 2020b; Xu et al., 2021; Zafrir et al., 2021; Li et al., 2022), structured pruning is more challenging and less explored. However, structured pruning is also more desirable in many practical scenarios, such as deploying these models on resource-constrained devices or providing fast and reliable services based on LLMs.

Existing work on structured pruning for LLMs focuses on BERT-like networks (Devlin et al., 2018) that consist of an encoder-decoder or an encoder-only architecture (Li et al., 2020; Xia et al., 2022; Zhang et al., 2022; Yao et al., 2021). These models are mainly used for natural language understanding (NLU) tasks, such as question answering, sentiment analysis, or natural language inference. Among the various methods, Block Movement Pruning (Lagunas et al., 2021) is a recent and popular technique that removes weight blocks based on movement. However, there is a lack of systematic research on structured pruning for decoder-only architectures such as GPT-2 Radford et al. (2019), GPT-3 Brown et al. (2020), or GPT-Neo Black et al. (2021), which are mainly used for natural language generation (NLG) tasks, such as text summarization, machine translation, or text completion. While there are some works that apply unstructured pruning (Li et al., 2022) or many kinds of orthogonal compression techniques to decoder-only LLMs (Wang et al., 2020a; Li et al., 2021; Edalati et al., 2022; Tao et al., 2022; Xu & Hu, 2022; Chen et al., 2021), there is no comprehensive evaluation of traditional structured pruning for these models on NLG tasks.

In this work, we compress decoder-only auto-regressive language models. Due to the lack of prior literature towards the same goal, we evaluate the performance of several general-domain pruning methods on NLG tasks, including magnitude and movement pruning. However, we find these methods can struggle or under-perform compared to naïve baselines, leading to the following question:

What determines the performance of structured pruning on generative language models?

We aim to fill this gap by conducting a systematic study of structured *fine-pruning* (pruning while finetuning) methods for decoder-only LLMs on NLG tasks[1], and further proposing a novel method that combines the strengths of different existing methods. Our main contributions are:

- To our knowledge, we perform the **first systematic evaluation** of several structured pruning methods to decoder-only LLMs on NLG tasks. We find that they only achieve marginal improvements over *randomly* selecting neurons in finetuning. We explain their limitations under our proposed analysis framework, and characterize their advantages and disadvantages via the metrics we evaluated.
- We propose an empirical analysis framework for structured pruning that relies on two fundamental measures of redundancy: **sensitivity** and **uniqueness**. Sensitivity reflects how much the removal of a network component affects the output of the model, while uniqueness reflects how much the information provided by a network component differs from others. Our framework allows us to understand and compare the behavior and performance of different pruning methods.
- Based on our analysis, we propose a new method, **Globally Unique Movement** (GUM), that aims to maximize both sensitivity and uniqueness by pruning network components based on their global movement and local uniqueness scores. We demonstrate that our method outperforms the existing methods on several NLG tasks and achieves competitive compression rates. We also conduct ablation studies to validate the effectiveness of our method components and design choices.

2 Background & Methodology

There are many general-domain pruning methods in existence. We focus on *fine-pruning*, a relevant technique for language models which performs automated gradual pruning (Zhu & Gupta, 2017) while fine-tuning. In this section, we introduce relevant terms and methodologies.

Notation and Background We shall define some notations for the MLP layers. Let $\sigma(\cdot) : \mathbb{R}^m \mapsto \mathbb{R}^m$ be an element-wise activation function (e.g. GeLU), and let $W_1 \in \mathbb{R}^{m\times d}$, $W_2 \in \mathbb{R}^{d\times m}$ be two weight matrices and $b \in \mathbb{R}^m$ be the bias vector. For an input token $x \in \mathbb{R}^d$, the MLP layer output of x is expressed as $\mathrm{MLP}(x) = x + W_2 h(x)$ with intermediate output $h(x) = \sigma(W_1 \mathsf{LN}(x))$, where LN represents layer normalization. The goal of this paper is to study the methods of reducing m, the intermediate dimension of the MLP layers, which is usually set at $m = 4d$ in most implementations. We use $\odot$ to denote element-wise multiplications. Lastly, we use $\mathcal{L}$ to denote the loss of the task.

Movement Pruning Movement Pruning (Sanh et al., 2020) is a popular fine-pruning method. In this paper, we focus on the *block* version of movement pruning (Lagunas et al., 2021), and we first introduce the original unstructured method. Let $\mathcal{L}(W)$ be the task loss with weight parameters W. For each weight parameter $W_{i,j}$, we compute a accumulated score $S_{i,j}$ at iteration T, by the following expression[2]:

$$S_{i,j}^{(T)} = -\eta_S \sum_{t\leq T} W_{i,j}^{(t)} \cdot \frac{\partial \mathcal{L}(W^{(t)})}{\partial W_{i,j}} \tag{1}$$

Afterwards, the scores are used to compute a mask M with entries $M_{i,j} \in \{0, 1\}$. And we apply the mask by $W' = M \odot W$, $b' = M \odot b$, and $U' = U \odot M$ to remove the masked weights.

[1]All code publicly available at **(removed for peer-review)**.

[2]Gradients are calculated straight-through to the mask scores, otherwise it is undefined (Bengio et al., 2013).

	Magnitude	Gradual Random	Hard Mvmt.	Soft Mvmt.	GUM
Score S	L_2-norms	Random (frozen)	Eq. 1	Eq. 1	Eq. 1
Selection	$\text{Top}_v(S)$	$\text{Top}_v(S)$	$\text{Top}_v(S)$	Threshold	$\text{Top}_v(S)$
Structure	Local	Local	Local	Global	Global
Regularization	None	None	$R(S)$	$R(S)$	$R(S) + R_{\text{sim}}(S)$ (Eq.4)
Criteria	Magnitude	Random	Sensitivity	Sensitivity	Sensitivity&Uniqueness

Table 1: Comparison of pruning methods used. $R(S)$ is defined in Section 2 and $R_{\text{sim}}(S)$ is described in Eq 4.

There are two ways to compute the mask M: $M = \text{Top}_v(S)$ for **hard movement** and $M = 1_{\text{sigmoid}(S)>\tau}$ for **soft movement**. τ and v are both hyperparameters, and $\text{Top}_v(S)$ is defined as:

$$\text{Top}_v(S)_i = \begin{cases} 1, & S_i \text{ in top } v\%, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Additionally, mask scores are regularized via a regularization term with multiplier λ_{mvp} of the form $R(S) = \lambda_{\text{mvp}} \sum_{i,j} \text{sigmoid}(S_{i,j})$. Hard movement prunes all layers by the same amount. Soft movement, however, allows for adaptive sparsity for different layers, which is known to be crucial for high-sparsity regimes He et al. (2018b); Mallya et al. (2018), and is seen to be the superior method for NLU tasks in Sanh et al. (2020). Block pruning expands on this method to operate on groups of weights by combining mask scores per block, allowing for structured pruning (Lagunas et al., 2021).

Magnitude Pruning We use a mask version of block magnitude pruning (a block extension of group-lasso, like Shen et al. (2021)) as the baseline. For each set G of parameters, we assign $S_G = (\sum_{(i,j)\in G} |W_{i,j}|^2)^{1/2}$ as the mask score and gradually prune groups with the smallest scores.

Gradual Random pruning Random pruning approaches have been explored previously (Yu et al., 2017; Blalock et al., 2020), and in particular gradual, random pruning (Gale et al., 2019) has been found to perform relatively well. We further explore random pruning in conjunction with distillation. Our gradual random method freezes S at random initialization for the duration of finetuning and prunes using $\text{Top}_v(S)$.

Knowledge Distillation In practice, pruning is often paired with knowledge distillation (Hinton et al., 2015) to boost performance. Distillation loss adds KL divergence between a teacher model and smaller student model. When used, we distill from a finetuned version of the model being pruned.

3 Fine-Pruning for Generative Language Models

We present our framework for understanding the redundancy of pruning methods. In this work, we focus on improving the seminal work of movement pruning proposed in Sanh et al. (2020). However, naïvely applying movement often results in incremental or worse performance compared to random. We dissect our results using a systematic framework and analyze their behaviors and properties.

3.1 Observations of Previous Pruning Methods

Soft Movement (BERT's Best Method) Struggles for GPT-like Models It is shown in Lagunas et al. (2021) that soft movement enjoys better performance over hard movement when block pruning encoder-decoder models. However, we find the method severely struggles when using the original implementation[3] on GPT-like models due to highly sensitive hyperparameters. For instance, the mask regularization parameter λ_{mvp} can either be too large and prune too aggressively, or too little, resulting in under-pruning as shown below. Even after grid searching λ_{mvp} we still find subpar performance, and given the high cost of training LLMs, we find this method impractical to use.

[3]Soft movement is the best to our knowledge at time of writing. Code is available at `https://github.com/huggingface/nn_pruning`. In this code, mask scores are added directly to the optimizer and are affected by optimizer algorithm or other hyperparameters. We use this code for a fair comparison between architectures, but manually updating the mask according to the definition might help (Zhang et al., 2022).

Model	Method	50% / + Distil	25% / + Distil	10% / + Distil
GPT-Neo-125m Finetuned: **65.92**	Soft	63.81 / 65.25	63.23 / 65.04	62.996* / 64.95*
	L_2-Magnitude	62.71 / 65.32	61.35 / 64.58	61.10 / 63.90
	Gradual Random	64.29 / 65.74	63.06 / 65.10	62.27 / 64.63
	Top_v	65.33 / 65.94	64.88 / 65.79	64.23 / 65.17
	GUM	63.88 / **66.23**	64.36 / **66.18**	63.81 / **65.65**

Table 2: **GPT-Neo-125m:** Performance in Acc_{lf} on the validation set for decreasing amount leftover on WikiSQL. GUM outperforms compared to other methods, soft movement struggles to match other methods, and gradual random nearly performs as well as Top_v. * indicates having 1-3% excess leftover neurons unpruned.

Model	Method	50% / + Distil	25% / + Distil	10% / + Distil
GPT-2-sm Finetuned: **70.32**	Soft	68.27 / 69.319	67.74 / 69.314	67.25* / 69.11*
	L_2-Magnitude	68.33 / 69.62	66.92 / 68.96	66.02 / 68.43
	Gradual Random	69.07 / 69.61	67.78 / 69.35	66.77 / 69.00
	Top_v	69.62 / 69.93	69.10 / 69.33	68.30 / 69.26
	GUM	68.62 / **70.38**	68.82 / **69.63**	68.07 / **69.46**

Table 3: **GPT-2-sm:** Performance in Acc_{lf} on the validation set for decreasing amount leftover on WikiSQL. * indicates having 1-3% excess leftover neurons unpruned.

Random Pruning Works Surprisingly Well One might expect movement to easily beat random pruning, however, we find their performances to only slightly differ or sometimes match, especially under distillation. Other works have noted random pruning's effectiveness (Gale et al., 2019), but we find the difference in generative tasks to be particularly slim. As shown in Tables 2 and 4, random pruning performs very close to both hard and soft movement pruning over WikiSQL and Wikitext datasets. Moreover, when combined with distillation, the gaps are largely closed between random pruning and other methods, which is also another intriguing observation itself, as we discuss below.

Distillation Closes the Gaps Between Different Methods As shown in Table 2 and Table 3, methods with very different performances would perform rather similar if distilled from a non-pruned, finetuned model. Indeed, both WikiSQL and Wikitext experiments in Table 4 and Table 5 showed that when the network has fewer left-over neurons (e.g., 10% or 25%), the difference of accuracies or perplexities often fall below half of the difference without distillation. This observation remains consistent across models of different sizes, architectures, and tasks. Results for GPT-neo with 1.3-billion parameters in Table 6 shows that pruning a larger model can still benefit from distillation. Knowledge distillation often boosts the performance of weaker methods even more, which might suggest the differences between methods are largely due to the inability to learn more diverse features set in fine-pruning, as suggested by the work of Allen-Zhu & Li (2020).

3.2 Two Types of Redundancy Measures: Sensitivity and Uniqueness

In order to understand why these pruning methods display such behaviors, we devise a framework to characterize the leftover neurons of pruned network based on two criteria: sensitivity and uniqueness[4]. Sensitivity captures how much a neuron contributes to the task objective $\mathcal{L}$, while uniqueness captures how much information it provides that is not already captured by other neurons. We formalize these notions of redundancy as follows:

Definition 3.1 (Redundancy Criteria) *Given a set of neurons $\{h_i(\cdot)\}_{i\in[m]}$ and input X, we call one neuron h_i* ***redundant*** *if it meets at least one of the following two conditions:*

[4]These are two known concepts in literature, but have not been both combined into one pruning method.

1. ***Sensitivity/Saliency****: the neuron is* ***not salient*** *if its outputs are either negligible or has small gradient when optimizing for the downstream task, mathematically described as*

$$\mathbb{E}\Big[|h_i(X) \cdot \frac{\partial \mathcal{L}}{\partial h_i(X)}|\Big] \approx 0$$

2. ***Uniqueness****: the neuron is* ***not unique*** *if its outputs could be reconstructed entirely with a linear combination of the outputs from other neurons, mathematically described as*

$$h_i(X) \in \text{span}(\{h_j(X)\}_{j \neq i}), \quad \textit{over all inputs } X$$

Intuitively, a sensitive neuron has outputs that greatly contribute to the final output, while a unique neuron has outputs which are different from that of others. These metrics are independent from one another, so a neuron could be highly salient but replaceable by other neurons, or it could be highly unique but ultimately contribute little to the network. Consider a toy example where two neurons h_i and h_j have the same non-zero weights and large gradient. Neuron h_i could easily be removed by doubling the outputs of h_j, so they are not unique, but both are highly salient.

The General Trade-off Between Saliency and Uniqueness Equipped with Definition 3.1, we find the following important trends. Figure 1 and Figure 2 show that without distillation, different methods often have a preference of focus on one of the redundancy measures. We now comment on trends across all tables (Table 2, 3, 4, 5). The best performing methods strike a balance between both measures. Under distillation, however, sensitivity seemingly concentrates across methods. Regardless of method, as more pruning occurs, sensitivity decreases and uniqueness increases in general. For individual methods, we can further dive deeper as below:

- *Magnitude pruning* universally scores worst on both metrics, explaining its poorer performance in all experiments. However, with distillation, gaps of sensitivity between methods noticeably decreases, which partially explains why distillation improves it significantly.
- *Random pruning* obtains similar distillation sensitivity and uniqueness, though slightly lower, to hard movement, lending credence to its overall high performance. However, sensitivity is markedly lower without distillation as is reflected in all tables. *We point to this as proof that hard movement does not target uniqueness.*
- *Soft movement pruning* also usually scores poorly on both metrics, and sometimes abysmally as in its sensitivity in Figure 1, again explaining its overall poor performance.

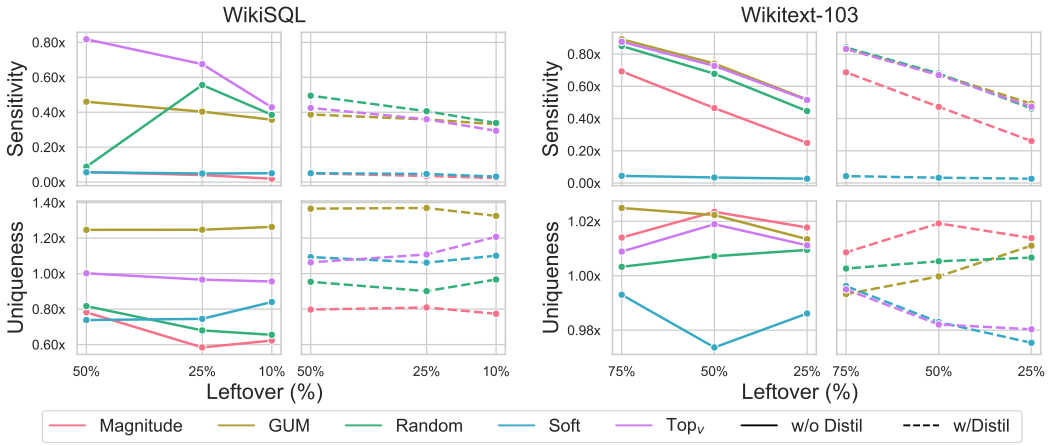

Figure 1: Sensitivity and Uniqueness measured on the training set for GPT-Neo-125m. The vertical axis is defined as the ratio of the corresponding metric between the pruned model and a baseline model (which is non-pruned and fully fine-tuned). We are able to use these graphs to analyze and compare the performance of different pruning methods. Details of measurements are given in Appendix D.

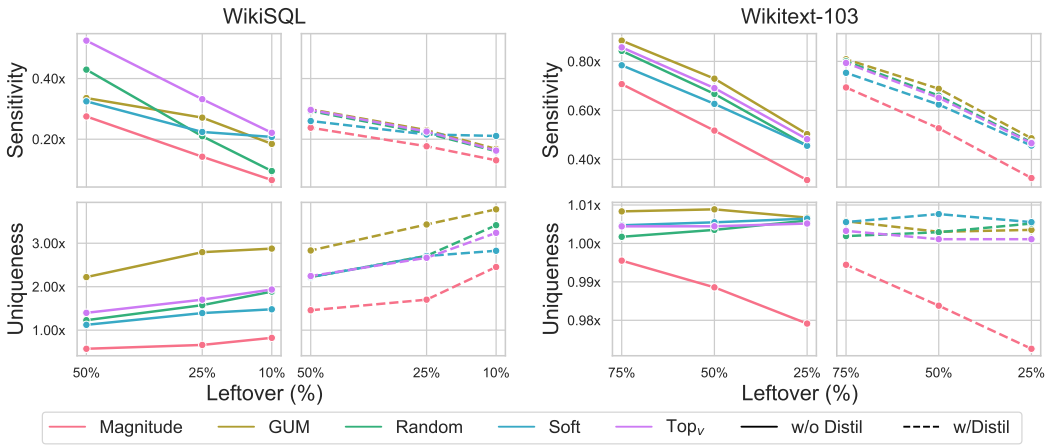

Figure 2: Sensitivity and Uniqueness measured on the training set for GPT-2-sm. The vertical axis is defined as the ratio of the corresponding metric between the pruned model and a baseline model (which is non-pruned and fully fine-tuned). Details of measurements are given in Appendix D.

- *Hard movement pruning* consistently obtains the highest sensitivity with not-far-behind uniqueness across different datasets and architectures. This explains the generally excellent performance when distillation is not used. However, when combined with distillation, the gaps of sensitivity between methods converge, and the advantage of hard movement fades.
- *GUM*, our proposed method, nearly always obtains best uniqueness while maintaining decent sensitivity, further improved using distillation, explaining its superiority across various tasks. However, GUM has a larger performance increase for GPT-Neo-125m than for GPT-2-sm on WikiSQL; this is explained in Figure 2 as pruned GPT-2 already has high baseline uniqueness for WikiSQL ($\sim$2x) so further increase incurs diminishing returns.

Given the training/validation split and general noise in the datasets, there are some outlier points, for instance, GUM's surprisingly poor distilled uniqueness for Wikitext in Figure 1. We observe higher absolute uniqueness on Wikitext in general (around 95% of neurons are unique per cosine similarity), meaning uniqueness varies over datasets and improving uniqueness is difficult.

4 Globally Unique Movement

After observing the lack of uniqueness amongst leftover neurons, we set out to improve the performance of hard movement. We introduce two techniques which together comprise Globally Unique Movement (GUM). In essence, we encourage a score-weighted uniqueness term by multiplying the score regularizer and the cosine similarity together, to obtain a balanced uniqueness and sensitivity of leftover neurons.

Tackling Non-Unique Redundancy Regularizing similarity or pruning via similarity is a well-explored topic (Ayinde et al., 2019; Zhu et al., 2018; Srinivas & Babu, 2015; Santacroce et al., 2020) and using existing techniques would increase uniqueness, however, it is possible to integrate cleanly with movement to insulate weights from the effects of regularization.

Our approach regularizes mask scores based on cosine similarity [5]. Cosine similarity between the outputs of any two neurons given input X (for example, a batch of tokens) is defined simply as

$$\mathrm{sim}(h_i(X), h_j(X)) = \frac{h_i(X)^\top h_j(X)}{\|h_i(X)\|_2 * \|h_j(X)\|_2} \tag{3}$$

[5]Solving for linear combinations of neurons during training is prohibitively expensive, so we consider cosine similarity as a "first-order" proxy.

Algorithm 1 Running Cosine Similarity Update

Require: a set of neurons $h_i(\cdot)$ for $i \in [m]$, inputs from a set $\mathcal{Z}$ (usually intermediate outputs of attention layers), an update multiplier λ_{sim};

1: Initialize running similarity $\mathbf{sim}^{(0)}(h_i, h_j) = 0$ for $i, j \in [m]$, running inner products $C_{i,j}^{(0)} = 0$, and running output vector norms $Q_i^{(0)} = 0$ for $i \in [m]$;
2: **while** still training **do**
3: Sample a input $X \in \mathcal{Z}$, compute the output vector neuron $h_j(X)$ for $j \in [m]$[7].
4: Update $C_{i,j}^{(t+1)} \leftarrow (1 - \lambda_{\text{sim}})C_{i,j}^{(t)} + \lambda_{\text{sim}} \cdot h_i(X)^\top h_j(X), \quad \forall i, j \in [m]$
5: Update $Q_i^{(t+1)} \leftarrow (1 - \lambda_{\text{sim}})Q_i^{(t)} + \lambda_{\text{sim}} \cdot \|h_i(X)\|_2^2, \quad \forall i \in [m]$
6: Update similarity by:

$$\mathbf{sim}^{(t+1)}(h_i, h_j) \leftarrow C_{i,j}^{(t+1)} / \sqrt{Q_i^{(t+1)} Q_j^{(t+1)}}, \quad \forall i, j \in [m]$$

7: **end while**

However, calculating similarity with only intra-batch estimates is noisy and unreliable, so we introduce a running version of its estimates in Algorithm 1 to obtain cosine similarity $\mathbf{sim}^{(t)}(h_i, h_j)$ between neurons $h_i(\cdot)$ and $h_j(\cdot)$. Now, we build on the regularization term $R_{\text{sim}}(S)$ of movement pruning to define a new regularization: Let N_{left} be the number of leftover neurons, for each group $j \in [m]$ and its corresponding score S_j, we define a term $U_j = \frac{1}{N_{\text{left}}} \sum_{i \in [m], i \neq j} \mathbf{sim}(h_j, h_i)$, and then we multiply U_j to the original terms in $R(S)$ to obtain

$$R_{\text{sim}}(S) = \lambda_{\text{mvp}} \sum_j U_j \cdot \text{sigmoid}(S_j) \tag{4}$$

Global Top$_v$ for Soft-Like Movement Hard movement removes the same amount of weights per layer independently. Global Top$_v$ instead uses Top$_v$ function on the set of all mask scores in the network jointly. Global Top$_v$ was originally explored for movement (Sanh et al., 2020) and was found to perform similarly. We find when used in conjunction with uniqueness regularization, Global outperforms Local. Global Top$_v$ intuitively allows for more flexibility when pruning. When pruning locally, it is necessary to choose the least common pruning percent - if one layer requires 50% neurons before severe degradation, all layers must keep 50%. Global comparison removes this loophole in a similar manner to soft movement [6].

5 Results

In this section, we present results on three different kinds of generative language modeling tasks: language modeling with Wikitext-103 Merity et al. (2016), text-to-text generation with the E2E NLG Challenge Dušek et al. (2020), and exact match measurable text-to-code generation with WikiSQL Zhong et al. (2017). Details and hyperparameters are listed in Appendix E. When distilling, the teacher model used is the finetuned model with the same parameters as the pretrained model. To ensure trends hold when scaling up, we present one experiment with GPT-Neo-1.3b in section 5. For all pruning amounts, we will present in terms of final percentage *leftover* - i.e., 75% of neurons remain after pruning. For soft movement, final prune percentage is shown in parentheses when it differs from desired prune percentage by a large amount.

In general, GUM is found to outperform Top$_v$ by a margin similar to the difference between Top$_v$ and gradual random pruning, with some exceptions. While small, we argue this gap shows the effectiveness of preserving neuron uniqueness alongside saliency.

Wikitext-103 Results on the Wikitext-103 dataset Merity et al. (2016), one of the most popular datasets for causal language modeling, are shown in Tables 4 and 5. Because performance on Wikitext-103 is in perplexity (PPL), it is a highly consistent and discriminatory dataset to prune on. We are unable to ever fully recover original model performance after pruning, suggesting that any compression increases output uncertainty.

[6] Appendix C shows an example pruning distribution for one pruned network.

Model	Method	75% / + Distil	50% / + Distil	25% / + Distil
GPT-Neo-125m Finetuned: **16.138**	Soft	17.814 / 17.651	19.470 / 19.053	21.169 / 20.4678*
	L_2-Magnitude	18.524 / 18.048	20.834 / 20.041	23.692 / 22.604
	Gradual Random	17.307 / 17.144	18.900 / 18.410	21.458 / 20.546
	Top_v	16.974 / 17.142	18.253 / 18.369	20.495 / 20.194
	GUM	**16.822** / 17.158	**17.881** / 18.314	20.059 / **19.833**

Table 4: **GPT-Neo-125m:** Performance in perplexity (PPL) on the validation set for decreasing amount leftover on Wikitext-103. * indicates having 1-3% excess leftover neurons unpruned.

Model	Method	75% / + Distil	50% / + Distil	25% / + Distil
GPT-2-sm Finetuned: **15.571**	Soft	16.754 / 16.950	18.261 / 18.051	19.948 / **19.473***
	L_2-Magnitude	17.399 / 17.414	19.595 / 19.178	22.593 / 21.667
	Gradual Random	16.574 / 16.823	17.974 / 17.862	20.444 / 19.798
	Top_v	16.363 / 16.730	17.611 / 17.742	20.016 / **19.663**
	GUM	**16.242** / 16.680	**17.444** / 17.692	19.877 / 19.681

Table 5: **GPT-2-sm:** Performance in perplexity (PPL) on the validation set for decreasing amount leftover on Wikitext-103. * indicates having 1-3% excess leftover neurons unpruned.

WikiSQL As opposed to the other datasets, WikiSQL Zhong et al. (2017) contains hard ground-truth labels for comparison via Exact Match (EM). Due to this, our best performance is achieved in WikiSQL, where GUM is able to remove up to 75% of neurons while maintaining performance on GPT-Neo. Results are shown in Tables 3 and 2. We also present results for GPT-Neo-1.3b only on WikiSQL in Table 6. Results for this experiment follow a similar trend to smaller models.

Model	Method	50%	25%	10%
GPT-Neo-1.3B Finetuned: **74.88**	Gradual Random	72.18 / **74.76**	70.38 / 73.83	68.56 / 72.77
	Top_v	73.33 / 74.75	72.18 / 74.54	71.14 / 73.77
	GUM	72.88 / 74.70	71.80 / **74.62**	71.35 / **74.157**

Table 6: **GPT-Neo-1.3B:** Performance in Acc_{lf} for decreasing amount leftover on WikiSQL.

E2E NLG Challenge We next test pruning on the E2E NLG Challenge Dušek et al. (2020). A highly popular dataset, performance in this domain is measured by a variety of metrics that all measure the quality of the output. It turns out the pruning on E2E is extremely inconsistent - removing even 90% of neurons can result in best performance. Additionally, nearly all pruning results perform better than the baseline, and increasing pruning more does not monotonically decrease performance.

We speculate these discrepancies are due to the open-endedness of the problem domain and underfitting the data. With these metrics, slightly different outputs can still be of similar quality. Due to these challenges, we do not test more models or combinations on this dataset. All results use distillation.

6 Additional Related Works

Our focus in this work is largely on modifying movement pruning given its demonstrated effectiveness over other methods.

General Domain Pruning Neural net pruning has been proposed years before the explosion of deep learning research (Janowsky, 1989; Mozer & Smolensky, 1988; Karnin, 1990), and are summarized in an outdated survey Reed (1993). Previous works have explored many approaches of pruning neural nets (Wen et al., 2016; Han et al., 2015b;a; Li et al., 2016). Recently, the *lottery ticket hypothesis*

Method & Leftover %	BLEU	NIST	METEOR	ROUGE_L	CIDEr
No Prune	68.22	8.6315	0.4479	0.7103	2.3141
Top_v 75%	68.26	8.6660	0.4486	0.7108	2.3120
Top_v 25%	68.80	8.6780	0.4487	0.7126	2.3238
Top_v 10%	68.15	8.6377	0.4472	0.7144	2.2955
GUM 75%	68.07	8.5698	0.4458	0.7090	2.2835
GUM 25%	68.22	8.6597	0.4495	0.7093	2.3230
GUM 10%	68.26	8.6684	0.4490	0.7109	2.3012

Table 7: **GPT-Neo-125m:** Validation results on the E2E NLG Challenge. Higher is better for all metrics. Even at 10% leftover, performance is similar to the baseline, for both Top_v and GUM.

Method & Leftover %	BLEU	NIST	METEOR	ROUGE_L	CIDEr
No Prune	67.34	8.5962	0.4598	0.7112	2.4399
Top_v 75%	66.79	8.5152	0.4576	0.7068	2.4350
Top_v 25%	67.54	8.5873	0.4603	0.7114	2.4347
Top_v 10%	66.85	8.4976	0.4578	0.7066	2.4217
GUM 75%	67.52	8.6014	0.4597	0.7094	2.4389
GUM 25%	66.24	8.4346	0.4567	0.7073	2.4136
GUM 10%	66.09	8.4032	0.4571	0.7064	2.4136

Table 8: **GPT-2-sm:** Validation results on the E2E NLG Challenge. Higher is better for all metrics. Even at 10% leftover, performance is relatively similar to the baseline, for both Top_v and GUM.

Frankle & Carbin (2018) proposed a new direction to prune at initialization instead. However, there is also a massive divergence of methods or claims that it is not worthwhile Liu et al. (2018); Blalock et al. (2020). Regardless, many strong techniques exist in modern incarnations across all kinds of architectures (Yang et al., 2016; Luo et al., 2017; He et al., 2018a).

Compressing Language Models Compressing LLMs in particular has spawned a unique kind of pruning. Given that LLMs first undergo pre-training on massive amounts of data, works such as Xu et al. (2021); Zafrir et al. (2021); Li et al. (2022) find ways to prune and finetune these models on downstream data. Building on automated gradual pruning (Zhu & Gupta, 2017) and learned threshold pruning (Azarian et al., 2020), movement pruning (Sanh et al., 2020) and further block movement (Lagunas et al., 2021) have become highly popular methods for *fine-pruning*, combining finetuning with pruning for overall best performance. Since then, many works have attempted to improve on movement (Yao et al., 2021; Zhang et al., 2022; Xia et al., 2022; Kwon et al., 2022). As previously mentioned, however, we are unable to find any comparable works systematically exploring structured pruning for decoder-only models.

7 Conclusion & Future Work

In this paper, we have performed an evaluation of structured pruning on generative language models, finding existing methods to improve over random pruning less than expected. In addition, we have proposed a framework for analyzing pruning methods in terms of uniqueness and saliency, two important criteria for preserving model quality and diversity. We have presented a novel method based on these metrics, GUM, for structured pruning of generative models, based on uniqueness regularization and global Top_v pruning. Our method can be applied to the MLP layers of various generative models, but there are still many open questions and challenges for pruning other components, such as attention heads or MoE modules. We also acknowledge the limitations of our method, which can reduce saliency and performance, suggesting possible directions for improving uniqueness pruning. Our work is an initial step towards understanding and improving structured pruning of generative models.

REFERENCES

Zeyuan Allen-Zhu and Yuanzhi Li. Towards understanding ensemble, knowledge distillation and self-distillation in deep learning. *arXiv preprint arXiv:2012.09816*, 2020.

Babajide O. Ayinde, Tamer Inanc, and Jacek M. Zurada. Regularizing deep neural networks by enhancing diversity in feature extraction. *IEEE Transactions on Neural Networks and Learning Systems*, 30(9):2650–2661, 2019. doi: 10.1109/TNNLS.2018.2885972.

Kambiz Azarian, Yash Bhalgat, Jinwon Lee, and Tijmen Blankevoort. Learned threshold pruning, 2020. URL https://arxiv.org/abs/2003.00075.

Yoshua Bengio, Nicholas Léonard, and Aaron Courville. Estimating or propagating gradients through stochastic neurons for conditional computation, 2013. URL https://arxiv.org/abs/1308.3432.

Sid Black, Leo Gao, Phil Wang, Connor Leahy, and Stella Biderman. GPT-Neo: Large Scale Autoregressive Language Modeling with Mesh-Tensorflow, March 2021. URL https://doi.org/10.5281/zenodo.5297715. If you use this software, please cite it using these metadata.

Davis Blalock, Jose Javier Gonzalez Ortiz, Jonathan Frankle, and John Guttag. What is the state of neural network pruning?, 2020. URL https://arxiv.org/abs/2003.03033.

Tom B. Brown, Benjamin Mann, Nick Ryder, Melanie Subbiah, Jared Kaplan, Prafulla Dhariwal, Arvind Neelakantan, Pranav Shyam, Girish Sastry, Amanda Askell, Sandhini Agarwal, Ariel Herbert-Voss, Gretchen Krueger, Tom Henighan, Rewon Child, Aditya Ramesh, Daniel M. Ziegler, Jeffrey Wu, Clemens Winter, Christopher Hesse, Mark Chen, Eric Sigler, Mateusz Litwin, Scott Gray, Benjamin Chess, Jack Clark, Christopher Berner, Sam McCandlish, Alec Radford, Ilya Sutskever, and Dario Amodei. Language models are few-shot learners, 2020. URL https://arxiv.org/abs/2005.14165.

Xuxi Chen, Tianlong Chen, Yu Cheng, Weizhu Chen, Zhangyang Wang, and Ahmed Hassan Awadallah. Dsee: Dually sparsity-embedded efficient tuning of pre-trained language models, 2021. URL https://arxiv.org/abs/2111.00160.

Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. Bert: Pre-training of deep bidirectional transformers for language understanding, 2018. URL https://arxiv.org/abs/1810.04805.

Ondřej Dušek, Jekaterina Novikova, and Verena Rieser. Evaluating the State-of-the-Art of End-to-End Natural Language Generation: The E2E NLG Challenge. *Computer Speech & Language*, 59: 123–156, January 2020. doi: 10.1016/j.csl.2019.06.009.

Ali Edalati, Marzieh Tahaei, Ahmad Rashid, Vahid Nia, James Clark, and Mehdi Rezagholizadeh. Kronecker decomposition for GPT compression. In *Proceedings of the 60th Annual Meeting of the Association for Computational Linguistics (Volume 2: Short Papers)*, pp. 219–226, Dublin, Ireland, May 2022. Association for Computational Linguistics. doi: 10.18653/v1/2022.acl-short.24. URL https://aclanthology.org/2022.acl-short.24.

Jonathan Frankle and Michael Carbin. The lottery ticket hypothesis: Finding sparse, trainable neural networks. 2018. doi: 10.48550/ARXIV.1803.03635. URL https://arxiv.org/abs/1803.03635.

Trevor Gale, Erich Elsen, and Sara Hooker. The state of sparsity in deep neural networks, 2019. URL https://arxiv.org/abs/1902.09574.

Song Han, Huizi Mao, and William J Dally. Deep compression: Compressing deep neural networks with pruning, trained quantization and huffman coding. *arXiv preprint arXiv:1510.00149*, 2015a.

Song Han, Jeff Pool, John Tran, and William Dally. Learning both weights and connections for efficient neural network. *Advances in neural information processing systems*, 28, 2015b.

Yihui He, Ji Lin, Zhijian Liu, Hanrui Wang, Li-Jia Li, and Song Han. Amc: Automl for model compression and acceleration on mobile devices. In *Proceedings of the European Conference on Computer Vision (ECCV)*, September 2018a.

Yihui He, Ji Lin, Zhijian Liu, Hanrui Wang, Li-Jia Li, and Song Han. Amc: Automl for model compression and acceleration on mobile devices, 2018b. URL https://arxiv.org/abs/1802.03494.

Geoffrey Hinton, Oriol Vinyals, and Jeff Dean. Distilling the knowledge in a neural network, 2015. URL https://arxiv.org/abs/1503.02531.

Steven A. Janowsky. Pruning versus clipping in neural networks. *Phys. Rev. A*, 39:6600–6603, Jun 1989. doi: 10.1103/PhysRevA.39.6600. URL https://link.aps.org/doi/10.1103/PhysRevA.39.6600.

E.D. Karnin. A simple procedure for pruning back-propagation trained neural networks. *IEEE Transactions on Neural Networks*, 1(2):239–242, 1990. doi: 10.1109/72.80236.

Woosuk Kwon, Sehoon Kim, Michael W. Mahoney, Joseph Hassoun, Kurt Keutzer, and Amir Gholami. A fast post-training pruning framework for transformers, 2022. URL https://arxiv.org/abs/2204.09656.

François Lagunas, Ella Charlaix, Victor Sanh, and Alexander M. Rush. Block pruning for faster transformers, 2021. URL https://arxiv.org/abs/2109.04838.

Bingbing Li, Zhenglun Kong, Tianyun Zhang, Ji Li, Zhengang Li, Hang Liu, and Caiwen Ding. Efficient transformer-based large scale language representations using hardware-friendly block structured pruning, 2020. URL https://arxiv.org/abs/2009.08065.

Hao Li, Asim Kadav, Igor Durdanovic, Hanan Samet, and Hans Peter Graf. Pruning filters for efficient convnets. *arXiv preprint arXiv:1608.08710*, 2016.

Tianda Li, Yassir El Mesbahi, Ivan Kobyzev, Ahmad Rashid, Atif Mahmud, Nithin Anchuri, Habib Hajimolahoseini, Yang Liu, and Mehdi Rezagholizadeh. A short study on compressing decoder-based language models, 2021. URL https://arxiv.org/abs/2110.08460.

Yuchao Li, Fuli Luo, Chuanqi Tan, Mengdi Wang, Songfang Huang, Shen Li, and Junjie Bai. Parameter-efficient sparsity for large language models fine-tuning, 2022. URL https://arxiv.org/abs/2205.11005.

Zhuang Liu, Mingjie Sun, Tinghui Zhou, Gao Huang, and Trevor Darrell. Rethinking the value of network pruning, 2018. URL https://arxiv.org/abs/1810.05270.

Jian-Hao Luo, Jianxin Wu, and Weiyao Lin. Thinet: A filter level pruning method for deep neural network compression. In *Proceedings of the IEEE International Conference on Computer Vision (ICCV)*, Oct 2017.

Arun Mallya, Dillon Davis, and Svetlana Lazebnik. Piggyback: Adapting a single network to multiple tasks by learning to mask weights, 2018. URL https://arxiv.org/abs/1801.06519.

Stephen Merity, Caiming Xiong, James Bradbury, and Richard Socher. Pointer sentinel mixture models, 2016.

Michael C Mozer and Paul Smolensky. Skeletonization: A technique for trimming the fat from a network via relevance assessment. In D. Touretzky (ed.), *Advances in Neural Information Processing Systems*, volume 1. Morgan-Kaufmann, 1988. URL https://proceedings.neurips.cc/paper/1988/file/07e1cd7dca89a1678042477183b7ac3f-Paper.pdf.

Alec Radford, Jeff Wu, Rewon Child, David Luan, Dario Amodei, and Ilya Sutskever. Language models are unsupervised multitask learners. 2019.

Russell Reed. Pruning algorithms-a survey. *IEEE transactions on Neural Networks*, 4(5):740–747, 1993.

Victor Sanh, Thomas Wolf, and Alexander M. Rush. Movement pruning: Adaptive sparsity by fine-tuning, 2020. URL https://arxiv.org/abs/2005.07683.

Michael L. Santacroce, Daniel Koranek, and Rashmi Jha. Detecting malware code as video with compressed, time-distributed neural networks. *IEEE Access*, 8:132748–132760, 2020. doi: 10.1109/ACCESS.2020.3010706.

Maying Shen, Pavlo Molchanov, Hongxu Yin, and Jose M Alvarez. When to prune? a policy towards early structural pruning. *arXiv preprint arXiv:2110.12007*, 2021.

Suraj Srinivas and R. Venkatesh Babu. Data-free parameter pruning for deep neural networks, 2015. URL https://arxiv.org/abs/1507.06149.

Chaofan Tao, Lu Hou, Wei Zhang, Lifeng Shang, Xin Jiang, Qun Liu, Ping Luo, and Ngai Wong. Compression of generative pre-trained language models via quantization. *arXiv preprint arXiv:2203.10705*, 2022.

Hanrui Wang, Zhekai Zhang, and Song Han. Spatten: Efficient sparse attention architecture with cascade token and head pruning, 2020a. URL https://arxiv.org/abs/2012.09852.

Ziheng Wang, Jeremy Wohlwend, and Tao Lei. Structured pruning of large language models. In *Proceedings of the 2020 Conference on Empirical Methods in Natural Language Processing (EMNLP)*. Association for Computational Linguistics, 2020b. doi: 10.18653/v1/2020.emnlp-main.496. URL https://doi.org/10.18653%2Fv1%2F2020.emnlp-main.496.

Wei Wen, Chunpeng Wu, Yandan Wang, Yiran Chen, and Hai Li. Learning structured sparsity in deep neural networks, 2016. URL https://arxiv.org/abs/1608.03665.

Mengzhou Xia, Zexuan Zhong, and Danqi Chen. Structured pruning learns compact and accurate models, 2022. URL https://arxiv.org/abs/2204.00408.

Dongkuan Xu, Ian E. H. Yen, Jinxi Zhao, and Zhibin Xiao. Rethinking network pruning – under the pre-train and fine-tune paradigm, 2021. URL https://arxiv.org/abs/2104.08682.

Guangxuan Xu and Qingyuan Hu. Can model compression improve nlp fairness, 2022. URL https://arxiv.org/abs/2201.08542.

Tien-Ju Yang, Yu-Hsin Chen, and Vivienne Sze. Designing energy-efficient convolutional neural networks using energy-aware pruning, 2016. URL https://arxiv.org/abs/1611.05128.

Zhewei Yao, Xiaoxia Wu, Linjian Ma, Sheng Shen, Kurt Keutzer, Michael W. Mahoney, and Yuxiong He. Leap: Learnable pruning for transformer-based models, 2021. URL https://arxiv.org/abs/2105.14636.

Ruichi Yu, Ang Li, Chun-Fu Chen, Jui-Hsin Lai, Vlad I. Morariu, Xintong Han, Mingfei Gao, Ching-Yung Lin, and Larry S. Davis. Nisp: Pruning networks using neuron importance score propagation, 2017. URL https://arxiv.org/abs/1711.05908.

Ofir Zafrir, Ariel Larey, Guy Boudoukh, Haihao Shen, and Moshe Wasserblat. Prune once for all: Sparse pre-trained language models, 2021. URL https://arxiv.org/abs/2111.05754.

Qingru Zhang, Simiao Zuo, Chen Liang, Alexander Bukharin, Pengcheng He, Weizhu Chen, and Tuo Zhao. Platon: Pruning large transformer models with upper confidence bound of weight importance, 2022. URL https://arxiv.org/abs/2206.12562.

Victor Zhong, Caiming Xiong, and Richard Socher. Seq2sql: Generating structured queries from natural language using reinforcement learning. *CoRR*, abs/1709.00103, 2017.

Michael Zhu and Suyog Gupta. To prune, or not to prune: exploring the efficacy of pruning for model compression, 2017. URL https://arxiv.org/abs/1710.01878.

Xiaotian Zhu, Wengang Zhou, and Houqiang Li. Improving deep neural network sparsity through decorrelation regularization. In *Proceedings of the Twenty-Seventh International Joint Conference on Artificial Intelligence, IJCAI-18*, pp. 3264–3270. International Joint Conferences on Artificial Intelligence Organization, 7 2018. doi: 10.24963/ijcai.2018/453. URL https://doi.org/10.24963/ijcai.2018/453.