IDP: ITERATIVE DIFFERENTIABLE PRUNING BASED ON ATTENTION FOR DEEP NEURAL NETWORKS

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ABSTRACT

Deep Neural network (DNN) pruning is an effective method to reduce the size of a model, improve the inference latency, and minimize the power consumption on DNN accelerators, at the risk of decreasing model accuracy. In this paper, we propose a novel differentiable pruning scheme, Iterative Differentiable Pruning or IDP which offers state-of-the-art qualities in model size, accuracy, and training cost. IDP creates attention-based pruning masks for a given sparsity target to achieve the state-of-the-art trade-offs between model accuracy and inference compute with negligible training overhead. We evaluated IDP on various computer vision and natural language processing tasks, and found that IDP delivers the state-of-the-art results. For MobileNet-v1 (which is a challenging DNN for pruning), IDP can achieve 68.2% top-1 ImageNet1k accuracy with 86.6% sparsity which is 2.3% higher accuracy than the latest state-of-the-art pruning algorithms. For ResNet18, IDP offers 69.5% top-1 ImageNet1k accuracy with 85.5% sparsity at the same training budget and 0.8% better top-1 accuracy than the state-of-the-art method. Also, IDP demonstrates over 83.1% accuracy on Multi-Genre Natural Language Inference with 90% sparsity for BERT, while the next best from the existing techniques shows 81.5% accuracy.

1 INTRODUCTION

While advanced deep neural networks (DNN) have exceeded human performance on many complex cognitive tasks (Silver et al., 2018), their deployment onto mobile/edge devices, such as watches or glasses, for enhanced user experience (i.e., reduced latency and improved privacy) is still challenging. Most such on-device systems are battery-powered and are heavily resource-constrained, thus requiring DNNs to have power/compute/storage efficiency (Wang et al., 2019; Wu et al., 2018; Howard et al., 2017; Vasu et al., 2022; Wang et al., 2020b).

Such efficiency can be accomplished by mixing and matching various techniques, such as designing efficient DNN architectures like MobileNet/MobileViT/ MobileOne (Sandler et al., 2018; Mehta & Rastegari, 2022; Vasu et al., 2022), distilling a complex DNN into a smaller architecture (Polino et al., 2018), quantizing/compressing the weights of DNNs (Cho et al., 2022; Han et al., 2016; J. Lee, 2021; Park & Yoo, 2020; Li et al., 2019; Zhao et al., 2019), and pruning near-zero weights (Peste et al., 2021; Kusupati et al., 2020; Liu et al., 2021; Zhang et al., 2022; Sanh et al., 2020; Zafrir et al., 2021; Zhu & Gupta, 2018; Wortsman et al., 2019). Also, pruning is known to be highly complementary to quantization/compression (Wang et al., 2020b). Training a larger model and then compressing it by pruning has been shown to be more effective in terms of model accuracy than training a smaller model (Li et al., 2020) from the beginning. However, pruning comes at the cost of degraded model accuracy, and the trade-off is not straightforward (Kusupati et al., 2020). For example, pruning an important weight can improve the inference speed, but may hurt the accuracy significantly (see Section B in Appendix for more discussion).

Hence, a desirable pruning algorithm should achieve high accuracy and accelerate inference for various types of networks without significant training overheads in costs and complexity. In this work, we propose a simple yet effective pruning technique, Iterative Differentiable Pruning, IDP based on an attention mechanism (Bahdana et al., 2015) that satisfies all of the above criteria. Our attention approach allows a pruning mask to be differentiable, and lets training-loss decide whether/how each weight will be pruned. Therefore, such a loss-driven differentiable pruning mask will help capture

	STR[a]	GraNet[b]	OptG[c]	ACDC[d]	MVP[e]	POFA[f]	IDP
Accuracy on Conv-Nets	✓	✓	✓✓	✓✓	?	?	✓✓✓
Accuracy on Transformers	?	?	✓	?	✓✓	✓✓	✓✓✓
Inference speed (MAC)	✓✓✓	✓	✓✓✓	✓	?	?	✓✓✓
Training speed	✓✓✓	✓✓	✓✓	✓	?	?	✓✓✓
Training stability	✓	✓✓	✓✓✓	✓✓✓	?	?	✓✓✓
Training flow	simple	complex	complex	complex	complex	complex	simple
Extra training parameters	a few	none	many	none	many	none	none

[a] Soft threshold weight re-parameterization for learnable sparsity (Kusupati et al., 2020).
[b] Sparse training via boosting pruning plasticity with neuro–regeneration (Liu et al., 2021).
[c] Optimizing gradient-driven criteria in network sparsity: Gradient is all you need (Zhang et al., 2022).
[d] AC/DC: alternating compressed/decompressed training of deep neural networks (Peste et al., 2021).
[e] Movement Pruning: Adaptive Sparsity by Fine-Tuning (Sanh et al., 2020).
[f] Prune Once for All: Sparse Pre-Trained Language Models (Zafrir et al., 2021).

Table 1: Comparison of the state-of-the-art pruning schemes and IDP: IDP can explore a good trade-off bewteen accuracy and inference speed without introducing new learnable parameters and with a simple/fast training flow.

the interactions among weights automatically without expensive mechanisms (Liu et al., 2021). Also, IDP requires neither additional learning parameters (Zhang et al., 2022) nor complicated training flows (Peste et al., 2021), yet offers a precise control on the target sparsity level (Kusupati et al., 2020) and pushes the state-of-the-art in pruning. Table 1 compares IDP with the latest state-of-the-art pruning schemes, and our major contributions include:

- A differentiable and parameter-free pruning algorithm based on attention.
- Efficiently pruning to offer a high-quality model for a given pruning target.
- The state-of-the-art results on both computer vision and natural language tasks.

2 Related Works

Trade-offs in Pruning: Pruning in DNN incurs a complex trade-off between model accuracy and inference speed in terms of MAC (mult-add operations) (Kusupati et al., 2020). A weight can contribute differently to the model accuracy, depending on the number of times it used for prediction (i.e., a weight in convolution filter for a large input) and the criticality of the layer it belongs to (i.e., a weight in a bottleneck layer). Please see Fig. 7 and Section B in Appendix for details. Therefore, even if two models are pruned to the same level, the accuracy and inference speed of each can be vastly different, which makes exploring the best trade-off challenging yet crucial in DNN pruning.

Unstructured Pruning: Unstructured schemes make individual and independent pruning decision for each weight to maximize the flexibility and minimize the accuracy degradation. Simple and gradual/iterative pruning based on the weight magnitude has been studied extensively (Zhu & Gupta, 2018; Gale et al., 2019; Frankle & Carbin, 2019; Han et al., 2015). In these schemes, once a weight is pruned, it does not have the *second* chance to become unpruned and improve the model quality. To address such challenges, RigL (Evci et al., 2020) proposes to grow a sparse network by reallocating the removed weights based on their dense gradients. Applying brain-inspired neurogeneration (i.e., unpruning some weights based on gradients) and leveraging pruning plasticity is proposed (Liu et al., 2021). Altering the phase of dense and sparse training to accomplish co-training of sparse and dense models is studied, which results in good model accuracies on vision tasks (Peste et al., 2021). LAMP (Lee et al., 2021) focuses on allocating the layer-wise sparsity level by minimizing model-level L2 distortion incurred by pruning. Unlike other magnitude-driven pruning, supermask training (Zhou et al., 2019) integrated with gradient-driven sparsity is proposed in (Zhang et al., 2022), where accumulated gradients are used to generate binary masks and straight-through estimator (Bengio et al., 2013) is used for backward propagation. Also, motivated by the lottery hypothesis (Frankle & Carbin, 2019), there is a body of efforts to prune a network in one-shot based on heuristics (Tanaka et al., 2020) or gradient-driven metrics (Wang et al., 2020a), but there exists a model accuracy gap compared with train-time pruning methods (Evci et al., 2020; Zhang et al., 2022).

Structured Pruning: Unstructured pruning limits inference latency speedup as it takes significant overhead to fetch irregular non-zero index matrices, suffers from poor memory access performance, and does not fit well on parallel computation (Anwar et al., 2017; Liu et al., 2022). Therefore, recent research extends unstructured pruning by imposing a particular sparsity pattern during pruning at

the cost of lower model predictive power, but increases the hardware performance during inference. One popular and effective form of structured pruning is channel pruning, where some channels with negligible effects on the model accuracy are discarded (He et al., 2017; Li et al., 2017; Kang & Han, 2020b). Clustering irregularly distributed weights with small magnitudes into structured blocks by reordering input/output dimension is proposed in (Ji et al., 2018). Using regularization to prune weights in a block is proposed in (Lagunas et al., 2021). Gradually increasing L2 regularization on unimportant filters decided by the L1-norm is proposed and extensively experimented in (Wang et al., 2021). N:M pruning is a more restrictive structured pruning method, where there are N zero weights out of every consecutive M weights (Zhou et al., 2021). Such hard constraints make it possible to have a compact memory layout and efficient inferences on hardware (Jeff Pool, 2021; Mishra et al., 2021; Zhou et al., 2021).

Differentiable Pruning: Using differentiable techniques for pruning gained popularity due to the advances in network architecture search methods, as well as network compression techniques (Liu et al., 2019; Chang et al., 2019; Cho et al., 2022). Using the first derivative of foothill function (Belbahri et al., 2019) as a mask function and applying L1 regularization on the pruning thresholds has been proposed for differentiable pruning (Ramakrishnan et al., 2020). However, it is not clear why the foothill function is the right choice (i.e., the mask value can exceed 1.0 and is not monotonic). DSA (Ning et al., 2020) finds the layer-wise pruning ratios in a differentiable fashion by computing a channel-wise keep probability drawn from the Bernoulli distribution. DSA requires solving a sub-problem in order to keep the expected sparsity ratio satisfied. Applying a differentiable technique for channel pruning was proposed (Kang & Han, 2020a) based on the operation-specific observation that a feature map with a large and negative batch mean will get deactivated (or zeroed) by ReLU activation function. A differentiable Markov process is studied for channel pruning, where a state represents a channel and the transitions from states accounts for the probability of keeping one channel unpruned under the condition that the other channel is also retained (Guo et al., 2020). AutoPrune (Xiao et al., 2019) introduces trainable auxiliary parameters (controlled by a regularizer) to generate a hard pruning mask differentiably using STE. Optimizing and training a per-layer pruning threshold with ReLU based on a dynamic re-parameterization method was proposed to allocate the sparsity across all layers (Kusupati et al., 2020), which shows competitive model accuracy and low inference overhead. IDP is a novel kind of differentiable pruning powered by attention-based soft mask to optimize individual weight masks per task-loss.

3 IDP: Iterative Differentiable Pruning

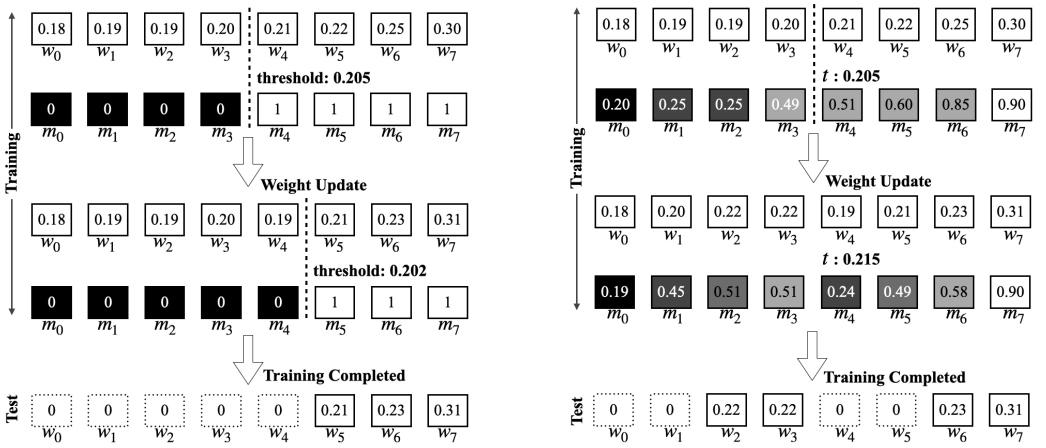
In this section, we introduce IDP by first providing the key ideas andinsights behind IDP in Section 3.1, and then explaining the details in Section 3.2. Then, we cover the training flow with IDP in Section 3.3.

3.1 Overview

Existing differentiable schemes focus on differentiable pruning budget allocation by training a differentiable pruning threshold based on marginal loss or L1-regularization (Kang & Han, 2020b; Ning et al., 2020). Meanwhile IDP directly generates an attention-based soft pruning mask for each weight to make the pruning process differentiable. Fig. 1 illustrates the differences with an example. Learning a pruning threshold is useful for global pruning budget allocation, as the threshold gets adjusted per the task loss as in Fig. 1 (a), but has the following drawbacks:

- Difficult to control a sparsity level, as the pruning threshold is not explicitly related to the sparsity because masks and the thresholds are not directly co-optimized. In Fig. 1 (a), after one weight update, the threshold is reduced from 0.205 to 0.202, but the sparsity is increased from 50% to 66% as w_5 gets decreased.
- Once a weight gets pruned during training, it does not get updated as the gradient is masked out. The bottom 4 weights $w_{\{0,1,2,3\}}$ get no weight update due to the zero masks, and can remain likely pruned through the end of training.

In the contrary, IDP allows all the weights to get updated through attention-based soft-mask as in Fig. 1 (b), providing higher flexibility and recovery from undesirable pruning. For example, consider the weight w_2 of a value 0.19 which would have been permanently pruned in (a). IDP discourages a



(a) Using a trainable threshold.

(b) Using a soft-mask by attention.

Figure 1: Unlike learning a threshold parameter for differentiable pruning (Kusupati et al., 2020; Ning et al., 2020) in (a), IDP generates a soft-mask using attention to accomplish differentiable pruning as in (b). The moment a weight is pruned in (a), the weight will not get any update as the mask zeros out the gradient, depriving the opportunity for better model training. However, the schemes in (a) ensure the training and test behaviors are identical, yet makes the sparsity control difficult. While IDP reveals different behaviors during training/test times because the test needs hard-masks, our attention-based mask allows a weight to recover from being pruned over the time, which yields higher model accuracies according to our results.

weight from being permanently pruned through the weight update, as still a scaled-down gradient is available. If a near-zero weight continues to get negative gradients over the time (even if it is scaled down by the soft-mask), it can eventually get unpruned at the end of training. In the same way, if a very large weight gets positive gradients many times enough to be near-zero, it will get pruned eventually, even if it was not pruned in the early stage. Hence, such gradual pruning decision over the time through training allows IDP to make better pruning decisions w.r.t. the task loss.

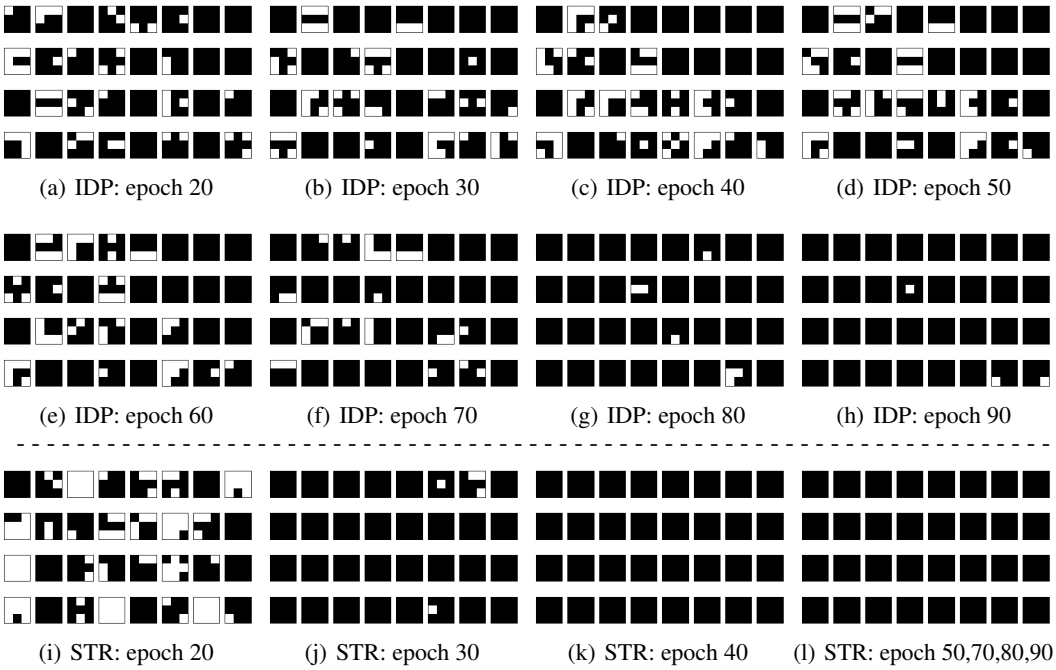
Such *soft* masking allows pruning decisions to be flipped multiple times during the entire training process, and such effects are compared between IDP and STR (Kusupati et al., 2020) (from Table 1) in Fig. 2 where the pruning decisions for the first Conv2d (3x3 kernels with 32 output channels) in MobileNet-v1 for the end-to-end ImageNet1k training are captured. The white cell means that the pruning decision has been flipped (from to-prune to not-to-prune or vice-versa), while the black cell means the decision has never changed, during the given epoch. Then, we can observe from Fig. 2 that while IDP in (a)-(h) continues to flip the decisions until the very late training stag, STR in (i)-(p) mostly finalizes the pruning decisions early.

3.2 IDP Algorithm

Instead of a hard-mask, IDP uses a soft-mask generated by attention to the two symbolic states, **"to-prune"** noted as Z or **"not-to-prune"** noted as M for a given weight w. Unlike the existing attention-based model optimizations such as (Cho et al., 2022), where the attention anchors are numerically defined, the attention to symbolic states is not straightforward to compute (i.e., Euclidean distance is not available directly), and thus requires a different approach.

Let us imagine continuous and differentiable functions, $z, m : \mathbb{R}_{[0,\infty]} \mapsto \mathbb{R}_{[0,1]}$ where z and m are the attentions to Z and M, respectively. Then, z and m must satisfy the following conditions to be used as attention-based soft mask for the magnitude-driven weight pruning:

- $z(|a|) > z(|b|)$ for any $|a| > |b|$
- $m(|a|) < m(|b|)$ for any $|a| > |b|$
- $z(w) + m(w) = 1$ for any w



(a) IDP: epoch 20 (b) IDP: epoch 30 (c) IDP: epoch 40 (d) IDP: epoch 50

(e) IDP: epoch 60 (f) IDP: epoch 70 (g) IDP: epoch 80 (h) IDP: epoch 90

(i) STR: epoch 20 (j) STR: epoch 30 (k) STR: epoch 40 (l) STR: epoch 50,70,80,90

Figure 2: The effects of IDP and STR (Kusupati et al., 2020) (from Table 1) for the first 3x3 Conv2d layer with 32 filters in MobileNet-v1 on ImageNet1k where each small rectangle represents one 3x3 kernel: For IDP, during the entire end-2-end training, we temporarily round the soft-mask value to make the pruning decisions. The white cell indicates such pruning decision for the corresponding weight has been flipped at least once during the particular epoch due to the differentiable soft-mask, and the black cell indicates the other case.

Accordingly, due to the monotonicity and continuity, there must exist $t \in \mathbb{R}_{\geq 0}$ such that $z(t) = m(t) = 0.5$ for the equal attention to Z and M, which leads to the following boundary conditions:

$$z(w) = \begin{cases} 1 & \text{if } w = 0 \\ 0 & \text{if } |w| = \infty \\ \frac{1}{2} & \text{if } |w| = t \end{cases}$$

One can use any function that satisfies all of the above conditions, and take $m(w)$ as a soft-mask of w for train-time pruning. In IDP, we uniquely identify t for a given prune ratio $r \in [0, 1)$ for a layer with a weight matrix W as follows based on the the pruning context:

$$W_h = topK(abs(W), (1-r)|W|) \tag{1}$$

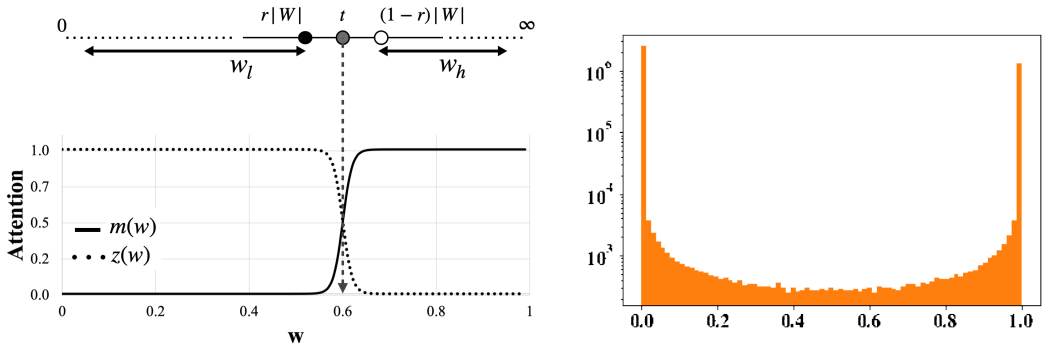
$$W_l = topK(-abs(W), r|W|) \tag{2}$$

$$t = \frac{min(W_h) + max(W_l)}{2} \tag{3}$$

where $topK(X, k)$ is selecting the largest k elements from a matrix X and $abs(X)$ is performing an element-wise absolute operation. Then, we propose the following to generate a soft-mask for a w:

$$[z(w), m(w)] = softmax(\frac{-[w^2, t^2]}{\tau}) \tag{4}$$

where τ is the temperature parameter (see Section C in Appendix for more discussions) and $m(w)$ can be directly used as a pruning mask during training. Fig. 3 (a) illustrates how t is obtained in IDP and a soft-mask is computed: essentially, t in gray, is in the exact middle of the largest pruned weight in black and the smallest unpruned weight in white when a hard-mask is applied for a given sparsity ratio r, thus giving us the equal attention to Z and M. Fig. 3 (b) shows the soft-mask distribution of the word-embedding layer of BERT (Devlin et al., 2019). Therefore, Eq. (4) satisfies all the constraints for z and m. Further, the softmax is fast enough to process a large number of weights. The soft-mask generation by IDP is stated in Algorithm 1, which has $O(W)$ runtime complexity.



(a) Attention plot by $w \in R_{[0,1]}$ with $t = 0.6$

(b) The soft-mask distribution example

Figure 3: Computing $z(w), m(w)$ for the attentions to Z and M with t for the equal attention to Z and M.

Algorithm 1 Computing a pruned weight matrix with IDP

1: **procedure** PRUNEMASK(W,r)
2: $W_h = topK(abs(W), (1-r)|W|)$
3: $W_l = topK(-abs(W), r|W|)$
4: $t = 0.5\{min(W_h) + max(W_l)\}$
5: $[Z, M] = softmax(\frac{-[W^2, [t,t,t,...]^2]}{\tau})$
6: **return** M
7: **end procedure**

In short, using a soft-mask by m enables the pruning decision for the weights around the pruning boundary (i.e., t) to be driven by a task loss through back-propagation rather than the weight value itself. On the contrary, a pruned weight will get zero gradient with a hard-mask once pruned.

3.3 TRAINING FLOW

In order to obtain t in Eq. (3), IDP needs a target pruning ratio r. The pruning ratio can be computed by selecting the top weights with larger magnitudes across all the layers and then instantly convert the selections into the per-layer ratios. Another way is to handcraft per-layer ratios, or reuse an existing configuration. Also, IDP is using the softmax operation which makes the *softness* concentrated over the weights around the t (as shown in Fig. 3). Hence, we gradually increase the target pruning ratio from 0 to r so that all low magnitude weights in the pruning range have a reasonable chance to use a soft-mask and settle down smoothly. For that purpose, we introduce a scaling step ϵ to let each weight have opportunities to leverage a soft-mask at least once, which leads to the training flow in Algorithm 2.

In lines 2-6, a normal training is performed for the first s epochs. Then, in lines 7 and 8, the per-layer target pruning ratio is computed by selecting the bottom $r \cdot |W|$ weights globally in terms of the magnitude. Then, in the remaining epochs, we use IDP to generate soft-masks as in the line 13, while gradually increasing the target ratio as in lines 9 and 10. Once the entire training is over, we binarize the last mask for each weight to output the fully pruned weight for inference as in the line 19.

4 EXPERIMENTAL RESULTS

We compared our **IDP** with state-of-the-art schemes on various computer vision and natural language models. All our experiments were on two x86 Linux nodes with eight NVIDIA V100 GPUs each. All pruning schemes in this section are for unstructured pruning.

Algorithm 2 Training flow for IDP

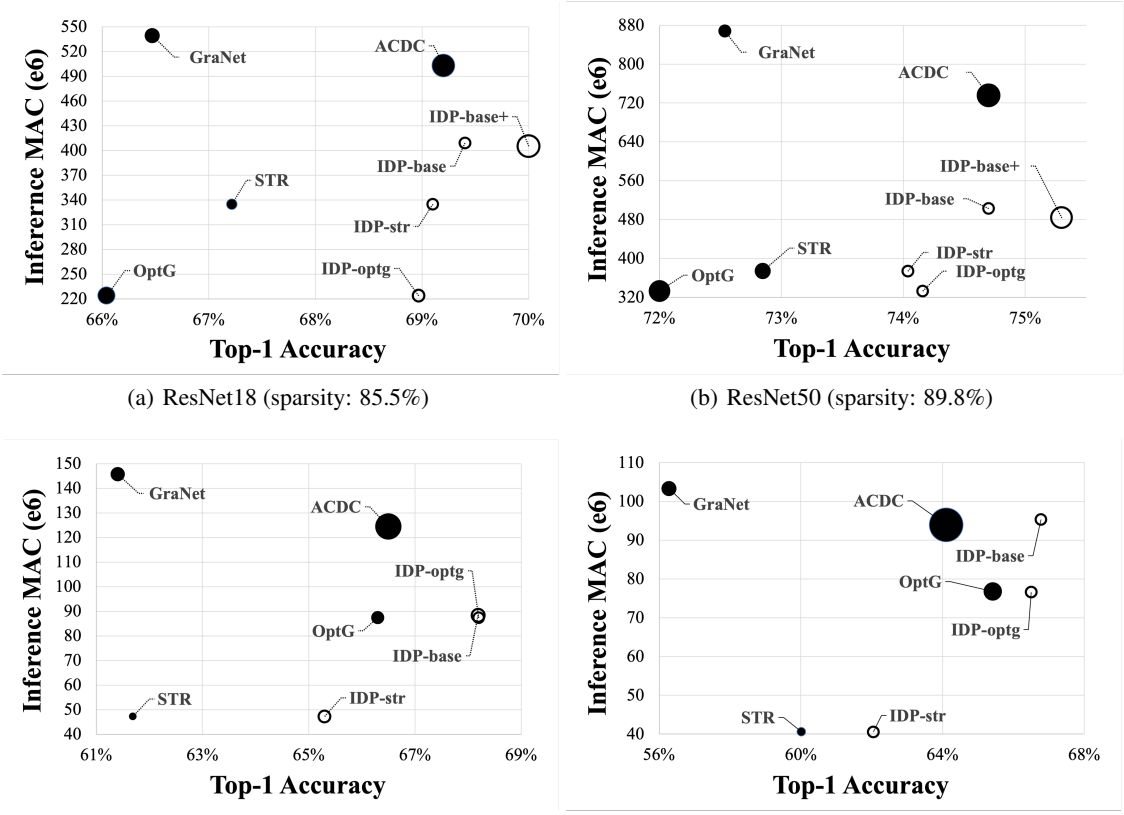
1: **procedure** TRAIN($\epsilon, s, r, W = [W_0, W_1, ...]$)
2: **for** epoch e in $[0, 1, 2, s)$ **do**
3: **for** each mini-batch **do**
4: forward with $[W_0, W_2, ...]$, backward and weight update
5: **end for**
6: **end for**
7: $W_p = topK(-abs(W), r \cdot |W|)$
8: $[r_0, r_1, ...] = [\frac{|W_p \cap W_0|}{|W_0|}, \frac{|W_p \cap W_1|}{|W_1|}, ...]$
9: **for** epoch e in $[s, s+1, s+2, ...]$ **do**
10: $[\hat{r_0}, \hat{r_1}, ...] = min(1, \epsilon \cdot (e - s)) \cdot [r_0, r_1, ...]$
11: **for** each mini-batch **do**
12: **for** $i \in \{0, 1, ...\}$ **do**
13: M_i= PruneMask($W_i, \hat{r_i}$)
14: $\hat{W}_i = M_i \circ W_i$
15: **end for**
16: forward with $[\hat{W}_0, \hat{W}_1, ...]$, backward and weight update
17: **end for**
18: **end for**
19: $W_i = \lfloor M_i \rceil \circ W_i, \forall i \in \{0, 1, ..\}$
20: **end procedure**

4.1 IMAGENET1K

We compared the proposed IDP with the latest prior arts, **STR** (Kusupati et al., 2020), **GMP** (Zhu & Gupta, 2018), **DNW** (Wortsman et al., 2019), **GraNet** (Liu et al., 2021), **OptG** (Zhang et al., 2022), and **ACDC** (Peste et al., 2021) on ResNet18, ResNet50, MobileNet-v1, and MobileNet-v2 (He et al., 2016; Howard et al., 2017; Sandler et al., 2018) with the ImageNet1k dataset (Deng et al., 2009). Since all of these schemes have been experimented only with ResNet50 and/or MobileNet-v1, we reproduced the pruning results in our controlled environment with the identical data augmentations by running the official implementations from the authors (Kusupati et al., 2020; Zhang et al., 2022; Peste et al., 2021; Liu et al., 2021) or verified implementations from the prior arts (Wortsman et al., 2019; Zhu & Gupta, 2018) as in Appendix E. Since the primary goal of pruning is to trade-off the model accuracy with the compute reduction as in Section 2, we measured the accuracies and inference-time Multiply-Accumulate Operation (MAC) on each experiment with layer fusion (i.e., BatchNorm folding), and mainly focused on the high-sparsification cases. In our experiments with ImageNet1k, all layers, including both the first and last layers, are pruned without any restriction. Also, we estimated training efficiency in wall-clock time by measuring the total GPU-hours (Chen et al., 2022), which is crucial to capture the algorithmic complexity and training flow overhead.

We applied not only the proposed hyper-parameters from the authors but also a set of further fine-tuned hyper-parameters. Also, since each algorithm used a different number of epochs and showed results at different sparsity levels, **a)** we ran **STR** first to set the target sparsity levels for all the networks for fair comparisons, because all other schemes can control the sparsity level precisely, **b)** we trained ResNet18/50 for 100 epochs and MobileNet-v1/v2 for 180 epochs following (Peste et al., 2021; Kusupati et al., 2020; Liu et al., 2021; Zhang et al., 2022) except **STR** (which diverged with more epochs for MobileNet-v1/v2). For **IDP**, we start pruning from the epoch 16 at the rate of 1.5% of the target sparsity per epoch for all the experiments which correspond to $s = 16$ and $\epsilon = 0.015$ in Algorithm 2. For detailed experiment configurations, please refer to Table 3. Every experiment began with a randomly initialized model (i.e., no pre-trained model). For **IDP**, we had the following variants to demonstrate the value of **IDP** with the same training overhead or with the same per-layer pruning budgets.

- **IDP-base** computes the target sparsity level by using weight magnitude globally, as in the lines 8 and 9 of Algorithm 2.
- **IDP-base+** is the same as **IDP-base** except it runs for additional epochs to consumes the similar total GPU hours with **ACDC**.



(a) ResNet18 (sparsity: 85.5%)

(b) ResNet50 (sparsity: 89.8%)

(c) MobileNet-v1 (sparsity: 86.6%)

(d) MobileNet-v2 (sparsity: 80.2%)

Network Sparsity	Method	Top-1 (%)	GPU$^{\$}$ hours	MAC ($\times e6$)
ResNet18 85.5%	Dense	69.8	91	1814.1
	GMP	65.2	118	263.5
	DNW	64.4	112	263.5
	GraNet*	66.0	108	539.6
	STR	66.7	93	334.6
	OptG*	65.5	151	223.7
	ACDC	68.7	194	502.8
	IDP-base	69.0	92	408.6
	IDP-base+	**69.5**	183	405.1
	IDP-str	68.6	92	334.7
	IDP-optg	68.5	95	223.7
MobileNet-v1 86.6%	Dense	70.9	151	568.7
	GraNet*	61.4	200	145.7
	STR	61.7	96	47.2
	OptG*	66.3	185	87.4
	ACDC	66.5	349	124.5
	IDP-base	**68.2**	153	88.3
	IDP-str	65.3	167	47.2
	IDP-optg	68.2	162	87.3

Network Sparsity	Method	Top-1 (%)	GPU$^{\$}$ hours	MAC ($\times e6$)
ResNet50 89.8%	Dense	76.1	135	4089.2
	GMP	73.6	263	419.0
	DNW	70.7	254	419.0
	GraNet*	72.5	175	868.0
	STR	72.8	227	373.7
	OptG*	72.1	322	333.0
	ACDC	74.7	346	735.6
	IDP-base	74.7	177	502.8
	IDP-base+	**75.3**	332	483.0
	IDP-str	74.0	177	373.7
	IDP-optg	74.2	181	332.9
MobileNetv-2 80.2%	Dense	71.9	162	300.8
	GraNet*	56.3	239	103.4
	STR	60.0	155	40.6
	OptG*	65.4	297	76.8
	ACDC	64.1	442	93.9
	IDP-base	**66.8**	193	95.3
	IDP-str	60.7	167	40.6
	IDP-optg	66.5	187	76.6

$^{\$}$ the total GPUs hours on all the GPUs in synchronous distributed training.
* used only one with 8 GPUs due to the limitations in the public code.

Figure 4: Accuracy vs. compute trade-offs: IDP-powered pruning (in white box markers) delivers the Pareto superiority to the other schemes (i.e., the top-bottom corner is the best trade-off) for ResNet18, ResNet50, and MobileNet-v1/v2 on ImageNet1k. The size of markers indicates the relative training overheads.

- **IDP-str/optg** uses the sparsification levels from **STR/OptG** as input to achieve the similar MAC: overwrite $[r0, r1, ...]$ in the line 8 of of Algorithm 2 with the results from **STR/OptG**.

Our experimental results are highlighted in Fig. 4, where the size of circles indicates the relative training overhead due to pruning. Note that we used only one single node with 8 GPUs due to the limitation in the official implementations for **GraNet** and **OptG**, thus both have the advantage of not having the inter-node communication cost. Also, each approach imposes a different level of training-time overhead, mainly due to the various complexities of training flow and pruning scheme itself as captured in Fig. 4. Especially, **ACDC** needs far more GPU hours for pruning than others. Overall results can be summarized as follows:

- **IDP** showed the best the model accuracy: **IDP-base** on ResNet18 delivered 69% Top-1 accuracy which is superior to other schemes but at higher MAC than only **STR** and **OptG**.
- **IDP** offered the better model accuracy for a given pruning target: With the custom sparsification target for each layer, **IDP-str/optg** demonstrated the 2-3% higher Top-1 accuracy at the same MAC, demonstrating the effectiveness of the proposed method.
- When we use the similar GPU hours for additional epochs with **ACDC** which is noted as **IDP-base+**, our method further improved the Top-1 accuracy from 69% to 69.5% for ResNet18 and from 74.7% to 75.3% for ResNet50 with slight fewer MACs.

Network	Sparsity	Validation dataset	Methods				
			OptG	GMP	MVP	POFA	IDP
Bert-base	90	matched	78.5	n/a	81.2	81.5	83.1
		mismatched	78.3	n/a	81.8	82.4	83.0
	94	matched	76.9	74.8	80.7	n/a	82.0
		mismatched	76.5	75.6	81.2	n/a	82.4

Table 2: **IDP** delivers the best accuracies on the BERT-based model with the MNLI (Multi-Genre Natural Language Inference) task of the GLUE benchmark.

4.2 GLUE NLP BENCHMARKS

We compared **IDP** with the state-of-the-art pruning results from **MVP** (Sanh et al., 2020) and **POFA** (Zafrir et al., 2021) (quoted from the respective papers) in addition to **OptG** (reproduced in our environment) on a BERT model (Devlin et al., 2019) for an NLP task, MNLI (Multi-Genre Natural Language Inference) task of the GLUE benchmark. Following the setups in **MVP** and **POFA**, we used the same batch size 32 per GPU (i.e., global mini-batch size of 512), excluded the embedding and the last linear layer from pruning, and trained the *bert-base-uncased* from HuggingFace from scratch with self-distillation. The teacher for the distillation is from the best checkpoint in the first 40 epochs and we use the weights of 0.95 on the distillation loss and 0.5 on the task loss. We could not use distillation for **OptG**, as it caused the out-of-memory error due to the extra-parameter overheads from both pruning and distillation. For detailed hyper-parameters, please refer to Table 3 in Appendix. Our experimental results in Table 2 can be summarized as follows:

- **OptG** shows better model accuracy only than **GMP** and worse than others in our setup.
- **IDP** outperformed all other methods for both MNLI validation datasets.

5 CONCLUSION

In this work, we proposed a differentiable pruning method, IDP which yields the state-of-the-art pruning quality on popular computer vision and natural language models. Our method requires no additional learning parameters, yet keeps the training flow simple and straightforward, making it a practical method for real-world scenarios. We plan to extend our differentiable pruning into quantization, making both jointly differentiable and optimizable by the task-loss.

6 ETHICS STATEMENT

The proposed technique does not incur any concern or penitential issues.

7

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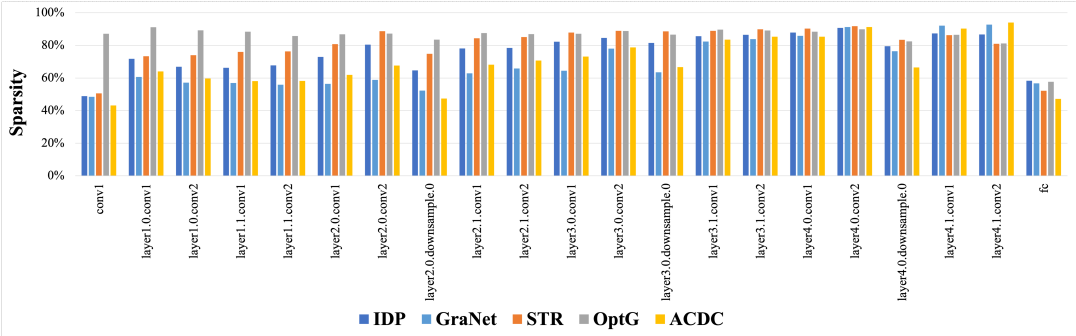
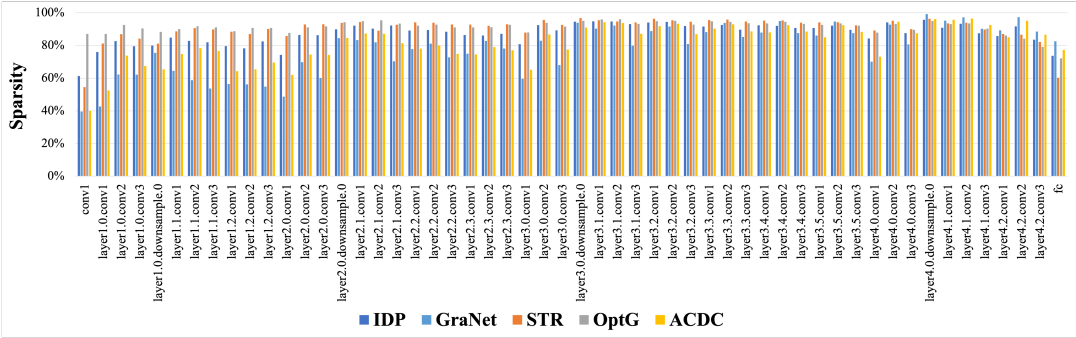
Network	Method	Batch size	#epochs	#wu	#GPUs	#Nodes	Main optimizer, scheduler	Mask optimizer, scheduler	other params
ResNet18	GraNet	128	100	5	8	1	SGD 0.9 1e-4 (0.0 for BN), cosine 0.1	n/a	init density: 0.5
	GMP	128	100	5	16	2	SGD 0.875 1e-5 , cosine 0.256	same as the main	
	STR	256	100	5	16	2	SGD 0.875 2.251757813e-5 , cosine 0.256	same as the main	init value: -3200
	OptG	256	100	5	16	2	SGD 0.9 1e-4, cosine 0.1	SGD 0.9 0, cosine 0.1	$\beta : 1.0$
	ACDC	256	100	5	8	1	SGD 0.875 3.051757813e-4, cosine 0.256	n/a	8 alterations
	IDP-base/str/optg	1024	100	5	16	2	SGD 0.9 1.4e-5, cosine 1.8	n/a	$\tau : 1e^{-4}, \epsilon : 0.015$
	IDP-base+	1024	200	5	16	2	SGD 0.9 1.4e-5, cosine 1.8	n/a	$\tau : 1e^{-4}, \epsilon : 0.015$
ResNet50	GraNet	128	100	5	8	1	SGD 0.9 1e-4 (0.0 for BN), cosine 0.1	n/a	init density: 0.5
	GMP	128	100	5	16	2	SGD 0.875 1e-5 , cosine 0.256	same as the main	
	STR	256	100	5	16	2	SGD 0.875 2.251757813e-5, cosine 0.256	same as the main	init value: -3200
	OptG	256	100	5	16	2	SGD 0.9 1e-4, cosine 0.1	SGD 0.9 0, cosine 0.1	$\beta : 1.0$
	ACDC	256	100	5	8	1	SGD 0.875 3.051757813e-4, cosine 0.256	n/a	8 alterations
	IDP-base/str/optg	1024	100	5	16	2	SGD 0.9 1.4e-5, cosine 1.8	n/a	$\tau : 1e^{-4}, \epsilon : 0.015$
	IDP-base+	1024	200	5	16	2	SGD 0.9 1.4e-5, cosine 1.8	n/a	$\tau : 1e^{-4}, \epsilon : 0.015$
MobileNet-v1	GraNet	128	180	5	8	1	SGD 0.9 1e-4 (0.0 for BN), cosine 0.1	n/a	init density: 0.5
	STR	256	100	5	16	2	SGD 0.875 3.751757813e-5, cosine 0.256	same as the main	init value: -12800
	OptG	256	180	5	16	2	SGD 0.9 4e-4, cosine 0.1	SGD 0.9 0, cosine 0.1	$\beta : 1.0$
	ACDC	256	180	5	8	1	SGD 0.875 3.051757813e-4, cosine 0.256	n/a	8 alterations
	IDP-base/str/optg	1024	180	5	16	2	SGD 0.9 1.4e-5, cosine 1.8	n/a	$\tau : 1e^{-4}, \epsilon : 0.015$
MobileNet-v2	GraNet	128	180	5	8	1	SGD 0.9 1e-4 (0.0 for BN), cosine 0.1	n/a	init density: 0.5
	STR	256	100	5	16	2	SGD 0.875 3.751757813e-5, cosine 0.256	same as the main	init value: -12800
	OptG	256	180	5	16	2	SGD 0.9 4-e4, cosine 0.05	SGD 0.9 0, cosine 0.05	$\beta : 1.0$
	ACDC	256	180	5	8	1	SGD 0.875 3.051757813e-4, cosine 0.256	n/a	8 alterations
	IDP-base/str/optg	1024	180	5	16	2	SGD 0.9 8e-6, cosine 0.8	n/a	$\tau : 1e^{-4}, \epsilon : 0.015$
Bert	GMP	Refer to Section 6 and Table 3 in (Sanh et al., 2020)							
	MOV	Refer to Section 6 and Table 3 in (Sanh et al., 2020)							
	POFA	Refer to Section E and Tables 5 and 6 in (Zafrir et al., 2021)							
	OptG	32	140	5	16	2	AdamW 1e-8, cosine 1e-4	SGD 0.9 0, cosine 1e-4	$\beta : 1.0$
	IDP	32	140	5	16	2	AdamW 1e-8, cosine 1e-4	n/a	$\tau : 1e^{-4}, \epsilon : 0.015$

SGD: momentum, weight decay, cosine: learning_rate, AdamW: epsilon, multiplicative: learning rate, gamma, #wu: the number of warm-up epochs.

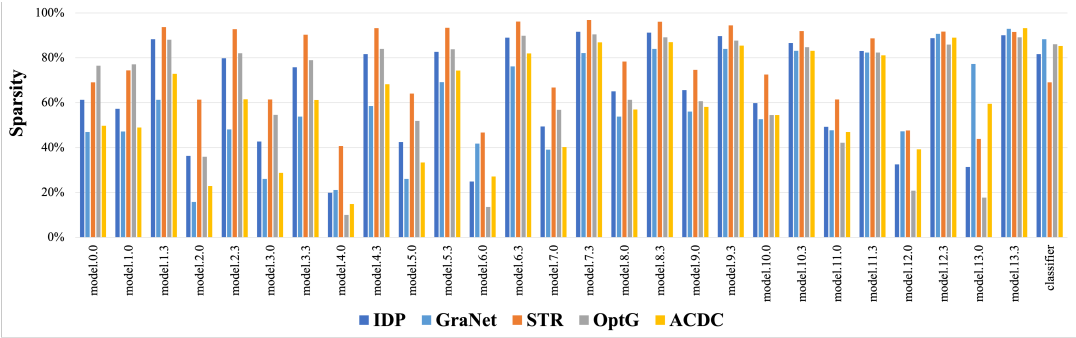
Table 3: The hyper-parameters in Section 4.



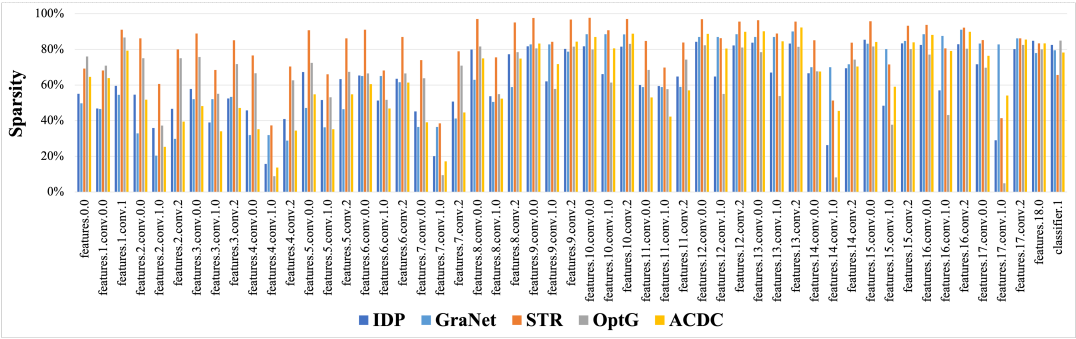
(a) ResNet18



(b) ResNet50

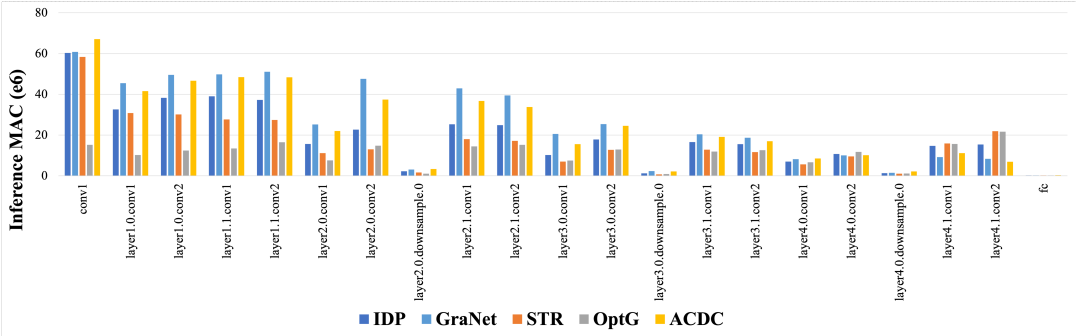


(c) MobileNet-v1

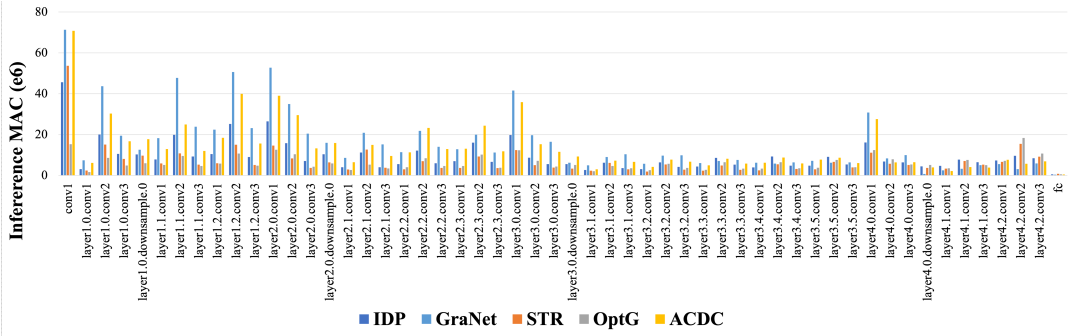


(d) MobileNet-v2

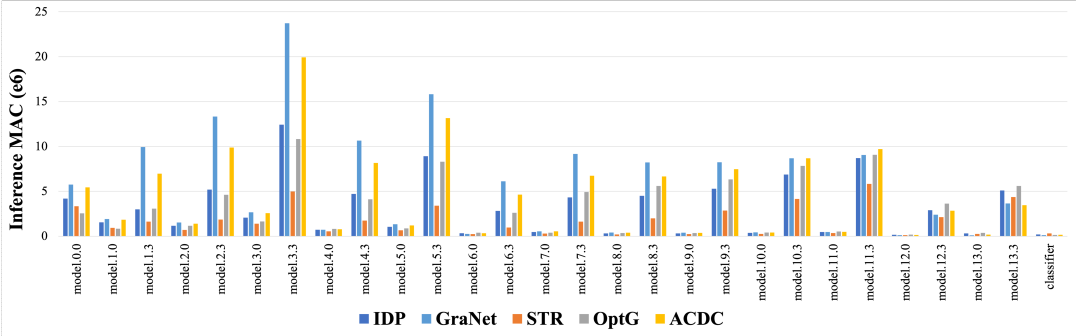
Figure 5: Layer-wise sparsity allocation from the experiments in Table 4.



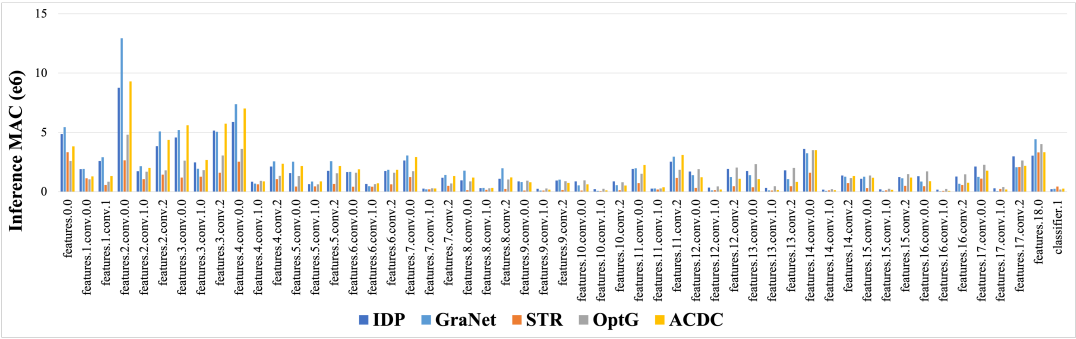
(a) ResNet18



(b) ResNet50



(c) MobileNet-v1



(d) MobileNet-v2

Figure 6: Layer-wise Inference MAC distribution from the experiments in Table 4.

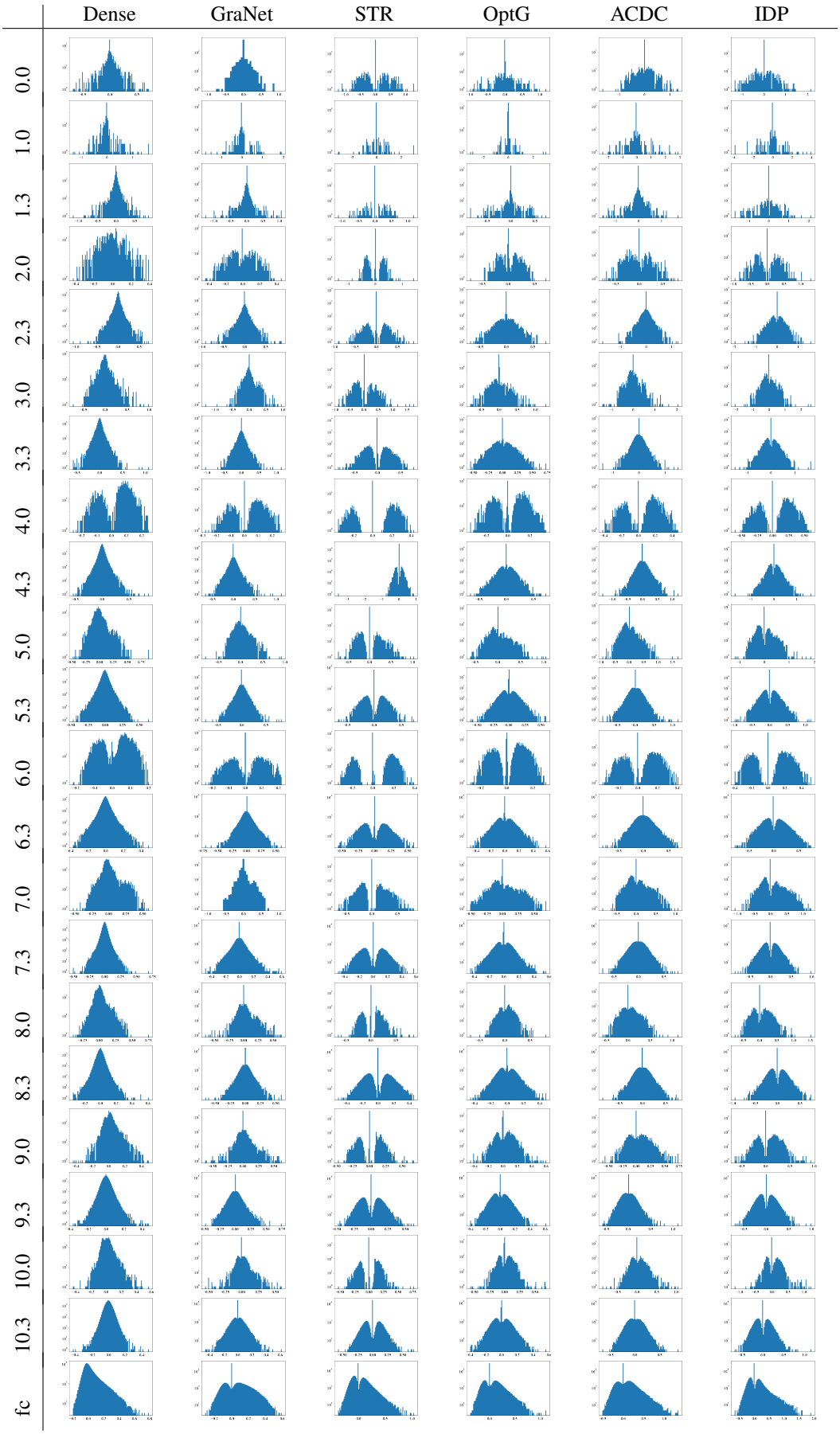


Table 4: The weight histograms in log scale for MobileNet-v1 in Table 4.

A TRAINING CONFIGURATIONS AND HYPER-PARAMETERS

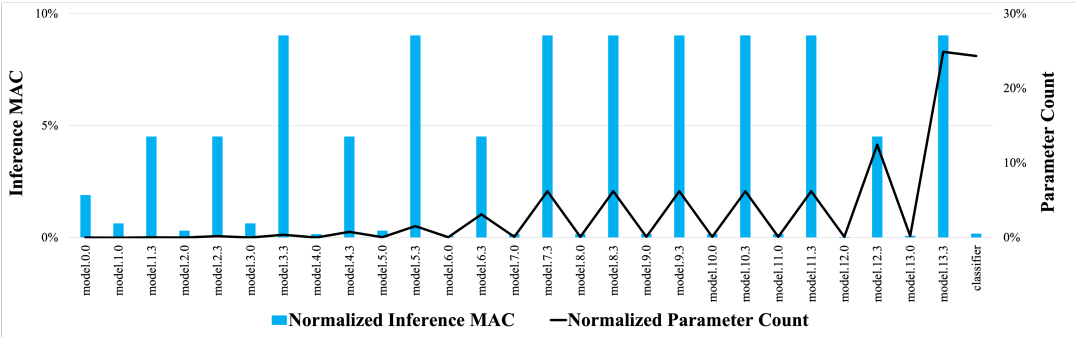
Since some techniques in Section 4 require extra training parameters and pruning scheduling as shown in Table 1, we disclose the training configurations and hyper-parameters we found the best in Table 3.

B TRADE-OFF IN PRUNING.

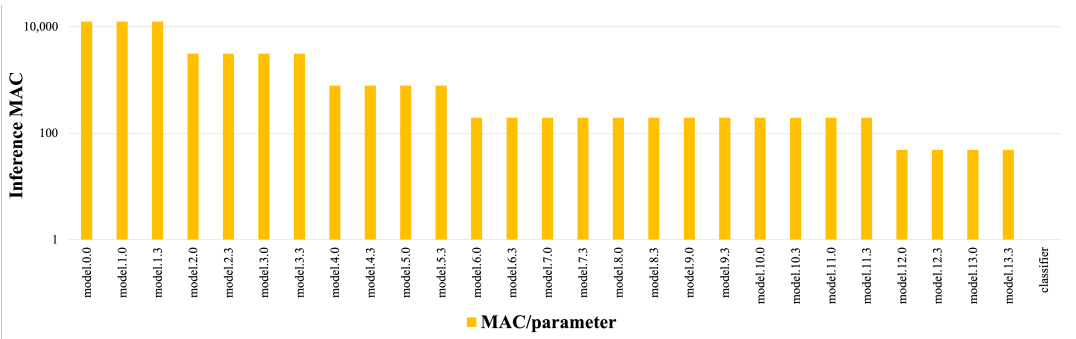
Pruning for DNN requires exploring a good trade-off between model accuracy and inference latency under a given pruning target. Such a challenge can be elaborated with the MobiletNet-v1 Dense case in Fig. 7 where the following observations can be made:

- The earlier layers have significantly fewer parameters than the later layers while still having comparable inference MACs as shown in (a). For example, the final classifier, which is a linear layer, has the lowest inference MAC but the 2nd largest parameters.
- When per-parameter inference MAC is computed as in (b) (which is in log-scale), we can easily see that the parameters in the earlier layers get much more involved in the inference than those in the later layers. For example, the MAC-per-parameter for the last classifier is only 1.

Then, with a given pruning target, one pruning scheme can favor heavily pruning the classifier, as it is easier to hit the target without affecting model accuracy much (i.e., each parameter shows up only once in the forward pass), but this would fail to reduce the inference MAC enough. Then, the other scheme may favor aggressively pruning the earlier layers to significantly minimize the inference latency at a much greater risk of degrading the model accuracy. Therefore, it is critical to find a good balance between accuracy and inference speed. According to our experimental results, IDP can accomplish such a balance using differential pruning w.r.t. the task loss.



(a) Normalized inference MAC and parameter count for each layer.



(b) The inference MAC per parameter for each layer.

Figure 7: Layer-wise Inference MAC and Parameters from the MobileNet-v1 Dense case in Table 4.

C ABLATION STUDY: HYPER-PARAMETER τ SEARCH

In the current IDP implementation, we use a global τ to control the level of softness in the pruning mask. Therefore, the selection of τ affects the model predictive power and should be carefully tuned. In order to explore the methodology for the τ search, we tried various values for MobileNet-v2 training, and the results are plotted in Fig. 8. The selection of τ affects the model predictive power as shown in Fig. 8 where there appears to be an optimal τ. For examples of MobileNet-v2, $\tau = 1e - 4$ is the best value and is used for all the experiments in Section 4.

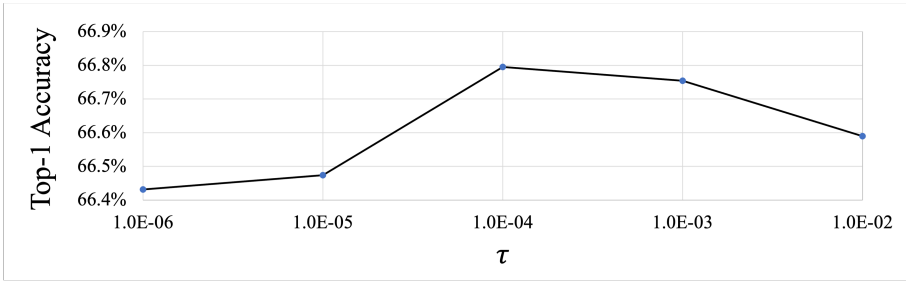


Figure 8: MobileNet-v2 with varying τ values.

Since, Fig. 8 shows a concave curve, one could use a binary search to find the best τ values w.r.t. the top-1 accuracy. Also, it could be possible to cast τ as a learnable parameter for each layer or apply some scheduling to improve the model accuracy further (as future work), but still both approaches need an excellent initial point which can be found using a binary search technique.

D ADDITIONAL RESULT FOR SECTION 4.1.

Different approaches made different sparsity allocations per the characteristics of the algorithm for a given pruning target, which results in complex trade-offs between model accuracy and inference speed. We report the detailed sparsity and inference MAC break-down for each layer in Fig. 5 and Fig. 6 on ImageNet1k and summarize our observations as follows:

- **OptG** prunes the early convolution layers quite aggressively in ResNet18 and ResNet50, which leads to very low inference MACs as shown in Fig. 4 (a) and (b), yet at the cost of the worse Top-1 accuracy. For example, the inference MAC of ResNet18 from **OptG** is more than 2x less than that from **ACDC**,
- Interestingly, **STR** becomes aggressive in pruning the early convolution layers in MobileNet-v1/v2, while **OptG** does not expose such behavior to MobileNet-v1/v2 (unlike it did for ResNet18/50). Such characteristics also favor the low inference latency over the model accuracy. Also, **STR** tends not to prune the last linear layer much as discussed in (Kusupati et al., 2020).
- Unlike **OptG** and **STR**, **ACDC** does not prune the early convolution layers much for the tested networks, but prunes somewhat actively for the late convolution and linear layers, which leads to high model accuracies at the cost of higher inference latencies.
- **IDP** is somewhat between **STR** and **ACDC** and modest across all layers in pruning allocation for all the networks, leading to superior accuracy and inference trade-offs. For example, the layers model.13.3 of MobileNet-v1 and features.17.conv.1.0 of MobileNet-v2 have the most difference among algorithms, and **IDP** is modest in pruning these two layers.
- **OptG** has very low inference MACs on the earlier layers of ResNet18 and ResNet50 due to its aggressive pruning on these as seen in Fig. 5 (a) and (b), which leads to the extremely low inference latencies as shown in Fig. 4 (a) and (b).
- **GraNet** tends to prune the earlier layers less but the later layers more in general which explains why **GraNet** shows the highest inference MACs in Fig. 4.

Table. 4 shows the pruned weight histograms of MobileNet-v1 from Table 4. We can observe that each algorithm affects the weight distribution in a slightly different way.

- **STR** prefers to split the distribution more widely than others. For the example of the layer 5.0, **STR** clearly separated the positive and negative weights with a wide gap centered at the zero, while others sis not, except **IDP** created a slight dip around the zero to create mild separation.
- **IDP** tends to spread out the sparsified weight distributions more than others. For the example of the fc layer, the weights from **IDP** range from -0.5 to 2.0, while those from others are from -0.5 to 1.5. On the other hand, **GraNet** tends to keep the weight distributions tight.

E CODE REFERENCES

- **Dense** https://pytorch.org/vision/stable/index.html
- **GradNet** https://github.com/VITA-Group/GraNet
- **OptG** https://github.com/zyxxmu/OptG
- **ACDC** https://github.com/IST-DASLab/ACDC
- **STR** https://github.com/RAIVNLab/STR
- **GMP** https://github.com/RAIVNLab/STR
- **DNW** https://github.com/RAIVNLab/STR