GROWING EFFICIENT DEEP NETWORKS BY STRUCTURED CONTINUOUS SPARSIFICATION

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ABSTRACT

We develop an approach to growing deep network architectures over the course of training, driven by a principled combination of accuracy and sparsity objectives. Unlike existing pruning or architecture search techniques that operate on full-sized models or supernet architectures, our method can start from a small, simple seed architecture and dynamically grow and prune both layers and filters. By combining a continuous relaxation of discrete network structure optimization with a scheme for sampling sparse subnetworks, we produce compact, pruned networks, while also drastically reducing the computational expense of training. For example, we achieve 49.7% inference FLOPs and 47.4% training FLOPs savings compared to a baseline ResNet-50 on ImageNet, while maintaining 75.2% top-1 accuracy — all without any dedicated fine-tuning stage. Experiments across CIFAR, ImageNet, PASCAL VOC, and Penn Treebank, with convolutional networks for image classification and semantic segmentation, and recurrent networks for language modeling, demonstrate that we both train faster and produce more efficient networks than competing architecture pruning or search methods.

1 INTRODUCTION

Deep neural networks are the dominant approach to a variety of machine learning tasks, including image classification (Krizhevsky et al., 2012; Simonyan & Zisserman, 2015), object detection (Girshick, 2015; Liu et al., 2016), semantic segmentation (Long et al., 2015; Chen et al., 2017) and language modeling (Zaremba et al., 2014; Vaswani et al., 2017; Devlin et al., 2018). Modern neural networks are overparameterized and training larger networks usually yields improved generalization accuracy. Recent work (He et al., 2016; Zagoruyko & Komodakis, 2016; Huang et al., 2017) illustrates this trend through increasing *depth* and *width* of convolutional neural networks (CNNs). Yet, training is compute-intensive, and real-world deployments are often limited by parameter and compute budgets.

Neural architecture search (NAS) (Zoph & Le, 2016; Liu et al., 2019; Luo et al., 2018; Pham et al., 2018; Savarese & Maire, 2019) and model pruning (Han et al., 2016; 2015; Guo et al., 2016) methods aim to reduce these burdens. NAS addresses an issue that further compounds training cost: the enormous space of possible network architectures. While hand-tuning architectural details, such as the connection structure of convolutional layers, can improve performance (Iandola et al., 2016; Sifre & Mallat, 2014; Chollet, 2017; Howard et al., 2017; Zhang et al., 2018; Huang et al., 2018), a principled way of deriving such designs remains elusive. NAS methods aim to automate exploration of possible architectures, producing an efficient design for a target task under practical resource constraints. However, during training, most NAS methods operate on a large *supernet* architecture, which encompasses candidate components beyond those that are eventually selected for inclusion in the resulting network (Zoph & Le, 2016; Liu et al., 2019; Luo et al., 2018; Pham et al., 2018; Savarese & Maire, 2019). Consequently, NAS-based training may typically be more thorough, but more computationally expensive, than training a single hand-designed architecture.

Model pruning techniques similarly focus on improving the resource efficiency of neural networks during inference, at the possible expense of increased training cost. Common strategies aim to generate a lighter version of a given network architecture by removing individual weights (Han et al., 2015; 2016; Molchanov et al., 2017) or structured parameter sets (Li et al., 2017; He et al., 2018; Luo et al., 2017). However, the majority of these methods train a full-sized model prior to pruning and, after pruning, utilize additional fine-tuning phases in order to maintain accuracy. Hubara et al. (2016)

(a) Growing CNN Layers and Filters (b) Epoch-wise Training Cost (c) Total Training Cost

Figure 1: **Growing Networks during Training.** We define an architecture configuration space and simultaneously adapt network structure and weights. **(a)** Applying our approach to CNNs, we maintain auxiliary variables that determine how to grow and prune both filters (*i.e.* channel-wise) and layers, subject to practical resource constraints. **(b)** By starting with a small network and growing its size, we utilize fewer resources in early training epochs, compared to pruning or NAS methods. **(c)** Consequently, our method significantly reduces the total computational cost of training, while delivering trained networks of comparable or better size and accuracy.

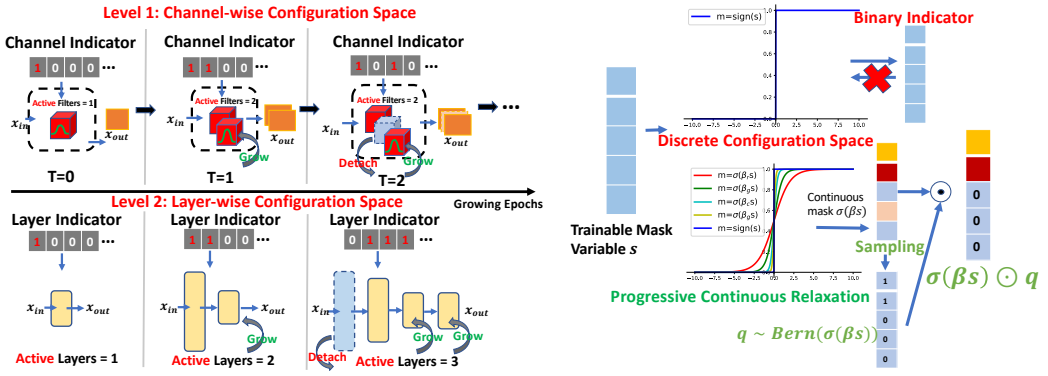
and Rastegari et al. (2016) propose the use of binary weights and activations, allowing inference to benefit from reduced storage costs and efficient computation through bit-counting operations. Yet, training still involves tracking high-precision weights alongside lower-precision approximations.

We take a unified view of pruning and architecture search, regarding both as acting on a configuration space, and propose a method to dynamically grow deep networks by continuously reconfiguring their architecture during training. Our approach not only produces models with efficient inference characteristics, but also reduces the computational cost of training; see Figure 1. Rather than starting with a full-sized network or a supernet, we start from simple seed networks and progressively adjust (grown and prune) them. Specifically, we parametrize an architectural configuration space with indicator variables governing addition or removal of structural components. Figure 2(a) shows an example, in the form of a two-level configuration space for CNN layers and filters. We enable learning of indicator values (and thereby, architectural structure) via combining a continuous relaxation with binary sampling, as illustrated in Figure 2(b). A per-component temperature parameter ensures that long-lived structures are eventually baked into the network's discrete architectural configuration.

While the recently proposed AutoGrow (Wen et al., 2020) also seeks to grow networks over the course of training, our technical approach differs substantially and leads to significant practical advantages. At a technical level, AutoGrow implements an architecture search procedure over a predefined modular structure, subject to hand-crafted, accuracy-driven growing and stopping policies. In contrast, we parameterize architectural configurations and utilize stochastic gradient descent to learn the auxiliary variables that specify structural components, while simultaneously training the weights within those components. Our unique technical approach yields the following advantages:

- **Fast Training by Growing** Training is a unified procedure, from which one can request a network structure and associated weights at any time. Unlike AutoGrow and the majority of pruning techniques, fine-tuning to optimize weights in a discovered architecture is optional. We achieve excellent results even without any fine-tuning stage.
- **Principled Approach: Learning by Continuation + Sampling** We formulate our approach in the spirit of learning by continuation methods, which relax a discrete optimization problem to an increasingly stiff continuous approximation. Critically, we introduce an additional sampling step to this strategy. From this combination, we gain the flexibility of exploring a supernet architecture, but the computational efficiency of only actually training a much smaller active subnetwork.
- **Budget-Aware Optimization Objectives** The parameters governing our architectural configuration are themselves updated via gradient decent. We have flexibility to formulate a variety of resource-sensitive losses, such as counting total FLOPs, in terms of these parameters,
- **Broad Applicability** Though we use progressive growth of CNNs in width and depth as a motivating example, our technique applies to virtually any neural architecture. One has flexibility in how to parametrize the architecture configuration space. We also show results with LSTMs.

We demonstrate these advantages while comparing to recent NAS and pruning methods through extensive experiments on classification, semantic segmentation, and word-level language modeling.



(a) Architectural Configuarion Space for CNNs (b) Optimization with Structured Continuation

Figure 2: **Technical Framework. (a)** We periodically restructure a CNN by querying binary indicators that define a two-level configuration space for filters and layers. **(b)** To make optimization feasible while growing networks, we derive these binary indicators from trainable continuous mask variables. We employ a structured extension of continuous sparsification (Savarese et al., 2019), combined with sampling. Binary stochastic auxiliary variables q, sampled according to $\sigma(\beta s)$, generate the discrete components active at a particular time.

2 Related Work

Network Pruning. Pruning methods can be split into two groups: those pruning individual weights and those pruning structured components. Individual weight-based pruning methods vary on the removal criteria. For example, Han et al. (2015) propose to prune network weights with small magnitude, and subsequently quantize those remaining (Han et al., 2016). Louizos et al. (2018) learn sparse networks by approximating ℓ_0-regularization with a stochastic reparameterization. However, sparse weights alone often only lead to speedups on dedicated hardware with supporting libraries.

In structured methods, pruning is applied at the level of neurons, channels, or even layers. For example, L1-pruning (Li et al., 2017) removes channels based on the norm of their filters. He et al. (2018) use group sparsity to smooth the pruning process after training. MorphNet (Gordon et al., 2018) regularizes weights towards zero until they are small enough such that the corresponding output channels are marked for removal from the network. Intrinsic Structured Sparsity (ISS) (Wen et al., 2018) works on LSTMs (Hochreiter & Schmidhuber, 1997) by collectively removing the columns and rows of the weight matrices via group LASSO. Although structured pruning methods and our algorithm share the same spirit of generating efficient models, we gain training cost savings by growing networks from small initial architectures instead of pruning a full-sized one.

Neural Architecture Search. NAS methods have greatly improved the performance achieved by small network models. Pioneering NAS approaches use reinforcement learning (Zoph et al., 2018; Zoph & Le, 2016) and genetic algorithms (Real et al., 2018; Xie & Yuille, 2017) to search for transferable network blocks whose performance surpasses many manually designed ones. However, such approaches require massive computation during the search — typically thousands of GPU days. To reduce computational cost, recent efforts utilize more efficient search techniques, such as direct gradient-based optimization (Liu et al., 2019; Luo et al., 2018; Pham et al., 2018; Tan et al., 2018; Cai et al., 2018; Wortsman et al., 2019). Nevertheless, most NAS methods perform search in a supernet space which requires more computation than training typically-sized architectures.

Network Growing. Network Morphism (Wei et al., 2016) searches for efficient deep networks by extending layers while preserving the parameters. Recently proposed Autogrow (Wen et al., 2020) takes an AutoML approach to growing layers. These methods either require a specially-crafted policy to stop growth (*e.g.,* after a fixed number of layers) or rely on evaluating accuracy during training, incurring significant additional computational cost.

Learning by Continuation. Continuation methods are commonly used to approximate intractable optimization problems by gradually increasing the difficulty of the underlying objective, for example by adopting gradual relaxations to binary problems. Wu et al. (2019); Xie et al. (2019b; 2020) use gumbel-softmax (Jang et al., 2017) to back-propagate errors during architecture search and spatial feature sparsification. Savarese et al. (2019) propose *continuous sparsification* to speed up pruning and ticket search (Frankle & Carbin, 2019). Despite the success of continuation methods in producing sparse networks upon the completion of training, they do not operate on sparse networks

during training and instead work with a real-valued relaxation. Postponing actual elimination of near zeroed-out components prevents naive application of these methods from reducing training costs.

3 METHOD

3.1 ARCHITECTURAL CONFIGURATION SPACE

A network topology can be seen as a directed acyclic graph consisting of an ordered sequence of nodes. Each node $\boldsymbol{x}_{in}^{(i)}$ is an input feature and each edge is a computation cell with *structured* hyperparameters (*e.g.,* filter and layer numbers in convolutional networks). An architectural configuration space can be parameterized by associating a mask variable $m \in \{0, 1\}$ with each computation cell (edge), which enables train-time pruning ($m = 1 \to 0$) and growing ($m = 0 \to 1$) dynamics.

As a running example, we consider a two-level configuration space for CNN architectures, depicted in Figure 2(a), that enables dynamically growing networks in both width (channel-wise) and depth (layer-wise). Alternative configuration spaces are possible; we defer to the Appendix details on how we parameterize the design of LSTM architectures.

CNN Channel Configuration Space: For a convolutional layer with l_{in} input channels, l_{out} output channels (filters) and $k \times k$ sized kernels, the i-th output feature is computed based on the i-th filter, *i.e.* for $i \in \{1, \ldots, l_{out}\}$:

$$\boldsymbol{x}_{out}^{(i)} = f(\boldsymbol{x}_{in}, \mathcal{F}^{(i)} \cdot \boldsymbol{m}_c^{(i)}) \,, \tag{1}$$

where $\boldsymbol{m}_c^{(i)} \in \{0, 1\}$ is a binary parameter that removes the i-th output channel when set to zero and f denotes the convolutional operation. $\boldsymbol{m}_c^{(i)}$ is shared across a filter and broadcasts to the same shape as the filter tensor $\mathcal{F}^{(i)}$, enabling growing/pruning of the entire filter. As Figure 2(a) (top) shows, we start from a *slim* channel configuration. We then query the indicator variables and perform *state transitions*: (1) When flipping an indicator variable from 0 to 1 for the first time, we grow a randomly initialized filter and concatenate it to the network. (2) If an indicator flips from 1 to 0, we temporarily detach the corresponding filter from the computational graph; it will be grown back to the its original position if its indicator flips back to 1, or otherwise be permanently pruned at the end of training. (3) For other cases, the corresponding filters either survive and continue training or remain detached pending the next query to their indicators. Our method automates architecture evolution, provided we can train the indicators.

CNN Layer Configuration Space: To grow network depth, we design a layer configuration space in which an initial shallow network will progressively expand into a deep trained model, as shown in Figure 2(a) (bottom). Similar to channel configuration space, where filters serve as basic structural units, we require a unified formulation to support the growing of popular networks with shortcut connections (*e.g.,* ResNets) and without (*e.g.,* VGG-like plain nets). We first introduce an abstract layer class f_{layer} as a basic structural unit, which operates on input features $\boldsymbol{x}_{in}$ and generates output features $\boldsymbol{x}_{out}$. f_{layer} can be instantiated as convolutional layers for plain nets or residual blocks for ResNets, respectively. We define the layer configuration space as:

$$\boldsymbol{x}_{out} = g(\boldsymbol{x}_{in}; f_{layer} \cdot \boldsymbol{m}_l^{(j)}) = \begin{cases} f_{layer}(\boldsymbol{x}_{in}), & \text{if} \quad \boldsymbol{m}_l^{(j)} = 1 \\ \boldsymbol{x}_{in}, & \text{if} \quad \boldsymbol{m}_l^{(j)} = 0 \end{cases} , \tag{2}$$

where $\boldsymbol{m}_l^{(j)} \in \{0, 1\}$ is the binary indicator for j-th layer f_{layer}, with which we perform state transitions analogous to the channel configuration space. Layer indicators have priority over channel indicators: if $\boldsymbol{m}_l^{(j)}$ is set as 0, all filters contained in the corresponding layer will be detached, regardless of the state their indicators. We do not detach layers that perform changes in resolution (*e.g.,* strided convolution).

3.2 GROWING WITH STRUCTURED CONTINUOUS SPARSIFICATION

We can optimize a trade-off between accuracy and structured sparsity by considering the objective:

$$\min_{w, m_{c,l}, f_{layer}} \quad L_E(g(f(\boldsymbol{x}; \boldsymbol{w} \odot \boldsymbol{m}_c); f_{layer} \cdot \boldsymbol{m}_l)) + \lambda_1 \left\| \boldsymbol{m}_c \right\|_0 + \lambda_2 \left\| \boldsymbol{m}_l \right\|_0 \,, \tag{3}$$

where f is the operation in Eq. (1) or Eq. (9) (in Appendix A.6), while g is defined in Eq. (2). $\boldsymbol{w} \odot \boldsymbol{m}_c$ and $f_{layer} \cdot \boldsymbol{m}_l$ are general expressions of structured sparsified filters and layers and L_E denotes a loss function (*e.g.,* cross-entropy loss for classification). The ℓ_0 terms encourage sparsity, while $\lambda_{1,2}$ are trade-off parameters between L_E and the ℓ_0 penalties.

Budget-aware Growing. In practice, utilizing Eq. (3) might require a grid search on λ_1 and λ_2 until a network with desired sparsity is produced. To avoid such a costly procedure, we propose a budget-aware growing process, guided by a target budget in terms of model parameters or FLOPs. Instead of treating λ_1 and λ_2 as constants, we periodically update them as:

$$\lambda_1 \leftarrow \lambda_1^{\text{base}} \cdot \Delta u, \lambda_2 \leftarrow \lambda_2^{\text{base}} \cdot \Delta u\,, \tag{4}$$

where Δu is calculated as the target sparsity u minus current network sparsity u_G, and λ_1^{base}, λ_2^{base} are initial base constants. In early growing stages, since the network is too sparse and Δu is negative, the optimizer will drive the network towards a state with more capacity (wider/deeper). The regularization effect gradually weakens as the network's sparsity approaches the budget (and Δu approaches zero). This allows us to adaptively grow the network and automatically adjust its sparsity level while simultaneously training model weights. Appendix A.1 provides more detailed analysis. Our experiments default to defining budget by parameter count, but also investigate alternative notions of budget.

Algorithm 1 : Optimization

Input: Data $\boldsymbol{X} = (\boldsymbol{x}_i)_{i=1}^n$, labels $\boldsymbol{Y} = (\boldsymbol{y}_i)_{i=1}^n$
Output: Grown efficient model G
Initialize: G, w, u, λ_1^{base} and λ_2^{base}.
Set $\boldsymbol{t}_s$ as all 0 vectors associating σ functions.
for epoch $= 1$ **to** T **do**
  Evaluate G's sparsity u_G and calculate $\Delta u = u - u_G$
  Update $\lambda_1 \leftarrow \lambda_1^{\text{base}} \cdot \Delta u$; $\lambda_2 \leftarrow \lambda_2^{\text{base}} \cdot \Delta u$ in Eq. (6) using Eq. (4)
  for $r = 1$ **to** R **do**
    Sample mini-batch x_i, y_i from $\boldsymbol{X}, \boldsymbol{Y}$
    Train G using Eq. (6) with SGD.
  end for
  Sample indicators $q_{c,l} \sim \text{Bern}(\sigma(\beta s_{c,l}))$ and record the index idx where q value is 1.
  Update $\boldsymbol{t}_s[idx] \mathrel{+}= 1$
  Update $\boldsymbol{\beta}$ using Eq. (7)
end for
return G

Learning by Continuation. Another issue in optimizing Eq. (3) is that $\|m_c\|_0$ and $\|m_l\|_0$ make the problem computationally intractable due to the combinatorial nature of binary states. To make the configuration space continuous and the optimization feasible, we borrow the concept of learning by continuation (Cao et al., 2017; Wu et al., 2019; Savarese et al., 2019; Xie et al., 2020). We reparameterize m as the binary sign of a continuous variable s: $\text{sign}(s)$ is 1 if $s > 0$ and 0 if $s < 0$. We rewrite the objective in Eq. (3) as:

$$\min_{\boldsymbol{w}, \boldsymbol{s}_{c,l} \neq 0, f_{layer}} L_E\Big(g\big(f(\boldsymbol{x}; \boldsymbol{w} \odot \text{sign}(\boldsymbol{s}_c)); f_{layer} \cdot \text{sign}(\boldsymbol{s}_l)\big)\Big) + \lambda_1 \|\text{sign}(\boldsymbol{s}_c)\|_1 + \lambda_2 \|\text{sign}(\boldsymbol{s}_l)\|_1\,. \tag{5}$$

We attack the hard and discontinuous optimization problem in Eq. (5) by starting with an *easier* objective which becomes *harder* as training proceeds. We use a sequence of functions whose limit is the sign operation: for any $s \neq 0$, $\lim_{\beta \to \infty} \sigma(\beta s) = \text{sign}(s)$ if σ is sigmoid function or $\lim_{\beta \to 0} \sigma(\beta s) = \text{sign}(s)$ if σ is gumbel-softmax $\frac{exp((-log(s_0)+g_1(s))/\beta)}{\sum_{j \in \{0,1\}} exp((-log(s_j)+g_j(s))/\beta)}$ (Jang et al., 2017), where $\beta > 0$ is a temperature parameter and $g_{0,1}$ is gumbel. By periodically changing β, $\sigma(\beta s)$ becomes harder to optimize, while the objectives converges to original discrete one.

Maintaining Any-time Sparsification. Although continuation methods can make the optimization feasible, they only conduct sparsification via a thresholding criterion in the inference phase. In this case, the train-time architecture is dense and not appropriate in the context of growing a network. To effectively reduce computational cost of training, we maintain a sparse architecture by introducing an 0-1 sampled auxiliary variable q based on the probability value $\sigma(\beta s)$. Our final objective becomes:

$$\min_{\boldsymbol{w}, \boldsymbol{s}_{c,l} \neq 0, f_{layer}} L_E\Big(g\big(f(\boldsymbol{x}; \boldsymbol{w} \odot \sigma(\beta \boldsymbol{s}_c) \odot \boldsymbol{q}_c); f_{layer} \cdot \sigma(\beta \boldsymbol{s}_l) \cdot \boldsymbol{q}_l\big)\Big) + \lambda_1 \|\sigma(\beta \boldsymbol{s}_c)\|_1 + \lambda_2 \|\sigma(\beta \boldsymbol{s}_l)\|_1\,, \tag{6}$$

where $\boldsymbol{q}_c$ and $\boldsymbol{q}_l$ are random variables sampled from $\text{Bern}(\sigma(\beta \boldsymbol{s}_c))$ and $\text{Bern}(\sigma(\beta \boldsymbol{s}_l))$, which effectively maintains any-time sparsification and avoids sub-optimal thresholding, as shown in Figure 2(b).

Improved Temperature Scheduler. In existing continuation methods, the initial β value is usually set as $\beta_0 = 1$ and a scheduler is used at the end of each training epoch to update β in all activation functions σ, typically following $\beta = \beta_0 \cdot \gamma^t$, where t is current epoch and γ is a hyperparameter (> 1 when σ is the sigmoid function, < 1 when σ is gumbel softmax). Both γ and t control the speed

Table 1: Comparison with the channel pruning methods L1-Pruning (Li et al., 2017), SoftNet (He et al., 2018), ThiNet (Luo et al., 2017), Provable (Liebenwein et al., 2020) and BAR (Lemaire et al., 2019) on CIFAR-10.

Model	Method	Val Acc(%)	Params(M)	FLOPs(%)	Train-Cost Savings($\times$)
VGG -16	Original	92.9 (+0.0)	14.99 (100%)	100	1$\times$
	L1-Pruning	91.8 (-1.1)	2.98 (19.9%)	19.9	2.5$\times$
	SoftNet	92.1 (-0.8)	5.40 (36.0%)	36.1	1.6$\times$
	ThiNet	90.8 (-2.1)	5.40 (36.0%)	36.1	1.6$\times$
	Provable	92.4 (-0.5)	0.85 (5.7%)	15.0	3.5$\times$
	Ours	**92.50 $\pm$ 0.10 (-0.4)**	**0.754 $\pm$ 0.005 (5.0%)**	**13.55 $\pm$ 0.03**	**4.95 $\pm$ 0.17** $\times$
ResNet -20	Original	91.3 (+0.0)	0.27 (100%)	100	1$\times$
	L1-Pruning	90.9 (-0.4)	0.15 (55.6%)	55.4	1.1$\times$
	SoftNet	90.8 (-0.5)	0.14 (53.6%)	50.6	1.2$\times$
	ThiNet	89.2 (-2.1)	0.18 (67.1%)	67.3	1.1$\times$
	Provable	90.8 (-0.5)	0.10 (37.3%)	54.5	1.7$\times$
	Ours	**90.91 $\pm$ 0.07 (-0.4)**	**0.096 $\pm$ 0.002 (35.8%)**	**50.20 $\pm$ 0.01**	**2.40 $\pm$ 0.09** $\times$
WRN -28 -10	Original	96.2 (+0.0)	36.5 (100%)	100	1$\times$
	L1-Pruning	95.2 (-1.0)	7.6 (20.8%)	49.5	1.5$\times$
	BAR(16x V)	92.0 (-4.2)	**2.3 (6.3%)**	**1.5**	2.6$\times$
	Ours	**95.32 $\pm$ 0.11 (-0.9)**	3.443 $\pm$ 0.010 (9.3%)	28.25 $\pm$ 0.04	**3.12 $\pm$ 0.11**$\times$

at which the temperature increases during training. Continuation methods with global temperature schedulers have been successfully applied in pruning and NAS. However, in our case, a global schedule leads to unbalanced dynamics between variables with low and high sampling probabilities: increasing the temperature of those less sampled at early stages may hinder their training altogether, as towards the end of training the optimization difficulty is higher. To overcome this issue, we propose a separate, structure-wise temperature scheduler by making a simple modification: for each mask variable, instead of using the current epoch number t to compute its temperature, we set a separate counter $\boldsymbol{t}_s$ which is increased only when its associated indicator variable is sampled as 1 in Eq. (6). We define our structure-wise temperature scheduler as

$$\boldsymbol{\beta} = \beta_0 \cdot \gamma^{\boldsymbol{t}_s}, \tag{7}$$

where $\boldsymbol{t}_s$ are vectors associated with the σ functions. Experiments use this separate scheduler by default, but also compare the two alternatives. Algorithm 1 summarizes our optimization procedure.

4 Experiments

We evaluate our method against existing channel pruning, network growing, and neural architecture search (NAS) methods on: CIFAR-10 (Krizhevsky et al., 2014) and ImageNet (Deng et al., 2009) for image classification, PASCAL (Everingham et al., 2015) for semantic segmentation and the Penn TreebBank (PTB) (Marcus et al., 1993) for language modeling. See dataset details in Appendix A.2. In tables, best results are highlighted in bold and second best are underlined.

4.1 Comparing with Channel Pruning Methods

Implementation Details. For fair comparison, we only grow filters while keeping other structured parameters of the network (number of layers/blocks) the same as unpruned baseline models. Our method involves two kinds of trainable variables: model weights and mask weights. For model weights, we adopt the same hyperparameters used to train the corresponding unpruned baseline models, except for setting the dropout keep probability for language modeling to 0.65. We initialize mask weights such that a single filter is activated in each layer. We train with SGD, an initial learning rate of 0.1, weight decay of 10^{-6} and momentum 0.9. Trade-off parameter λ_1^{base} is set to 0.5 on all tasks; λ_2 is not used since we do not perform layer growing here. We set σ as the sigmoid function and γ as $100^{\frac{1}{T}}$ where T is the total number of epochs.

VGG-16, ResNet-20, and WideResNet-28-10 on CIFAR-10. Table 1 summarizes the models produced by our method and competing channel pruning approaches. Note that training cost is calculated based on overall FLOPs during pruning and growing stages. Our method produces sparser networks with less accuracy degradation, and, consistently saves more computation during training — a consequence of growing from a simple network. For a aggressively pruned WideResNet-28-10, we observe that BAR (Lemaire et al., 2019) might not have enough capacity to achieve negligible accuracy drop, even with knowledge distillation (Hinton et al., 2015) during training. Note that we

Table 2: Comparison with channel pruning methods: L1-Pruning (Li et al., 2017), SoftNet (He et al., 2018) and Provable (Liebenwein et al., 2020) on ImageNet.

Model	Method	Top-1 Acc(%)	Params(M)	FLOPs(%)	Train-Cost Savings(×)
ResNet -50	Original	76.1 (+0)	23.0 (100%)	100	1(×)
	L1-Pruning	74.7 (-1.4)	19.6 (85.2%)	77.5	1.1(×)
	SoftNet	74.6 (-1.5)	N/A	58.2	1.2(×)
	Provable	**75.2 (-0.9)**	15.2 (65.9%)	70.0	1.2(×)
	Ours	**75.2 (-0.9)**	**14.1 (61.2%)**	**50.3**	**1.9**(×)

Table 3: Results comparing with AutoGrow (Wen et al., 2020) on CIFAR-10 and ImageNet.

Dataset	Methods	Variants	Found Net	Val Acc(%)	Depth	Sparse Channel
CIFAR-10	Ours	*Basic3ResNet*	23-29-31	**94.50**	**83**	✓
		Plain3Net	11-14-19	**90.99**	**44**	✓
	AutoGrow	*Basic3ResNet*	42-42-42	94.27	126	✗
		Plain3Net	23-22-22	90.82	67	✗
ImageNet	Ours	*Bottleneck4ResNet*	5-6-5-7	**77.41**	**23**	✓
		Plain4Net	3-4-4-5	**70.79**	**16**	✓
	AutoGrow	*Bottleneck4ResNet*	6-7-3-9	77.33	25	✗
		Plain4Net	5-5-5-4	70.54	19	✗

report our method's performance as mean ± standard deviation, computed over 5 runs with different random seeds. The small observed variance shows that our method performs consistently across runs.

ResNet-50 and MobileNetV1 on ImageNet. To validate effectiveness on large-scale datasets, we grow, from scratch, filters of the widely used ResNet-50 on ImageNet; we do not fine-tune. Table 2 shows our results best those directly reported in papers of respective competing methods. Our approach achieves 49.7% inference and 47.4% training cost savings in terms of FLOPs while maintaining 75.2% top-1 accuracy, without any fine-tuning stage. Appendix A.4 show our improvements on the challenging task of growing channels of an already compact MobileNetV1. In addition, Figure 3 shows the top-1 accuracy/FlOPs trade-offs for MobileNetV1 on ImageNet, demonstrating that our method dominates competing approaches.

Deeplab-v3-ResNet-101 on PASCAL VOC. Appendix A.5 provides semantic segmentation results.

2-Stacked-LSTMs on PTB: We detail the extensions to recurrent cells and compare our proposed method with ISS based on vanilla two-layer stacked LSTM in Appendix A.6. As shown in Table 8, our method finds more compact model structure with lower training cost, while achieving similar perplexity on both validation and test sets.

4.2 Comparing with AutoGrow

Implementation Details. We grow both filters and layers. We follow AutoGrow's settings in exploring architectural variations that define our initial seed network, layer-wise configuration space and basic structural units f_{layer}: *Basic3ResNet*, *Bottleneck4ResNet*, *Plain3Net*, *Plain4Net*. Different from the initialization of AutoGrow using full-sized filters in each layer, our channel-wise configuration space starts from single filter and expands simultaneously with layers. Appendix A.7 contains a detailed comparison of seed architectures. For training model weights, we adopt the hyperparameters of the ResNet or VGG models corresponding to initial seed variants. For layer-wise and channel-wise mask variables, we initialize the weights such that only a single filter in each layer and one basic unit in each stage (*e.g.,* BasicBlock in *Basic3ResNet*) is active. We use SGD training with initial learning rate of 0.1, weight decay of 10^{-6} and momentum of 0.9 on all datasets. The learning rate scheduler is the same as for the corresponding model weights. Trade-off parameters λ_1^{base} and λ_2^{base} are set as 1.0 and 0.1 on all datasets. For fair comparison, we finetune our final models with 40 epochs and 20 epochs on CIFAR-10 and ImageNet, respectively.

Results on CIFAR-10 and ImageNet. Table 3 compares our results to those of AutoGrow. For all layer-wise growing variants across both datasets, our method consistently yield a better depth and width configuration than AutoGrow, in terms of accuracy and training/inference costs trade-off. Regarding the training time of *Bottleneck4ResNet* on ImageNet, AutoGrow requires 61.6 hours for the growing phase and 78.6 hours for fine-tuning on 4 TITAN V GPUs, while our method takes 48.2 and 31.3 hours, respectively. Our method offers 43% more train-time savings than AutoGrow. We not only require fewer training epochs, but also grows from a single filter to a relatively sparse network, while AutoGrow always keeps full-sized filter sets without any reallocation.

4.3 COMPARING WITH NAS METHODS

As a fair comparison with NAS methods involving search and re-training phases, we also divide our method into growing and training phases. Specifically, we grow layers and channels from the *Bottleneck4ResNet* seed architecture directly on ImageNet by setting $\lambda_1^{base} = 2.0$, $\lambda_2^{base} = 0.1$ and the parameter budget under 7M. Then we resume training the grown architecture and compare with existing NAS methods in terms of parameters, top-1 validation accuracy and V100 GPU hours required by the search or growing stages, as shown in Table 4. Note that DARTS (Liu et al., 2018) conducts search on CIFAR-10, then transfers to ImageNet instead of direct search. This is because DARTS operates on a supernet by including all the candidate paths and suffers from GPU memory explosion. In terms of epoch-wise FLOPs, results shown in Figure 1(c) are for training an equivalent of ResNet-20 on CIFAR-10 in comparison with DARTS and Provable channel pruning approach (Liebenwein et al., 2020). Also note that the EfficientNet-B0 architecture, included in Table 4, is generated by grid search in the MnasNet search space, thus having the same heavy search cost. To achieve the reported performance, EfficientNet-B0's utilizes additional squeeze-and-excitation (SE) (Hu et al., 2018) modules, AutoAugment (Cubuk et al., 2018) as well as much longer re-training epochs on ImageNet.

Table 4: Performance comparing with NAS methods AmoebaNet-A (Real et al., 2018), MnasNet (Tan et al., 2019), EfficientNet-B0 (Tan & Le, 2019), DARTS (Liu et al., 2018) and ProxylessNet (Cai et al., 2018) on ImageNet.

Method	Params	Top-1	Search/Grow Cost
AmoebaNet-A	5.1M	74.5%	76K GPU hours
MnasNet	**4.4M**	74.0%	40K GPU hours
EfficientNet-B0	5.3M	**77.1**% (+SE)	40K GPU hours
DARTS	4.7M	73.1%	N/A
ProxylessNet(GPU)	7.1M	75.1%	200 GPU hours
Ours	6.8M	74.3%	**80** GPU hours
Ours	6.7M	74.8%	110 GPU hours
Ours	6.9M	75.1%	140 GPU hours

ProxylessNet still starts with a over-parameterized supernet but applies a pruning-like search method by binarizing the architecture parameters and forcing only one path to be activated at search-time, enabling directly searching on ImageNet and achieving $200\times$ more search cost savings than MnasNet. Contrasting with ProxylessNet, our method progressively adds filters and layers to simple seed architectures while maintaining sparsification, which leads to savings of not only epoch-wise computation but also memory consumption, enabling faster, larger-batch training. As such, we further save 45% of the GPU search hours while achieving comparable accuracy-param tradeoffs.

4.4 ANALYSIS

Training Cost Savings. Figure 4 illustrates our sparsification dynamics, showing epoch-wise FLOPs while growing a ResNet-20. Appendix A.8 presents additional visualizations. Even with fully parallel GPU hardware, starting with few filters and layers in the network will ultimately save wall-clock time, as larger batch training (Goyal et al., 2017) can always be employed to fill the hardware.

Figure 5, shows validation accuracy, model complexity, and layer count while growing *Basic3ResNet*. Complexity is measured as the model parameters ratio of AutoGrow's target model. At the end of 160 epochs, our method's validation accuracy is 92.36% , which is higher than AutoGrow's 84.65% at 360 epochs. We thus require fewer fine-tuning epochs to achieve a final 94.50% accuracy on CIFAR.

Table 5: Comparison with random pruning baseline on CIFAR-10.

Model	Method	Val Acc(%)	Params(M)
VGG-16	Random	90.01 ± 0.69	0.770 ± 0.050
	Ours	$\mathbf{92.50 \pm 0.10}$	0.754 ± 0.005
ResNet-20	Random	89.18 ± 0.55	0.100 ± 0.010
	Ours	$\mathbf{90.91 \pm 0.07}$	0.096 ± 0.002
WRN-28-10	Random	92.26 ± 0.87	3.440 ± 0.110
	Ours	$\mathbf{95.32 \pm 0.11}$	3.443 ± 0.010

Budget-Aware Growing. In Figure 6, for ResNet-20 on CIFAR-10, we compare architectures obtained by (1) *uniform pruning*: a naive pre-defined pruning method that prunes the same percentage of channels in each layer, (2) *ours*: variants of our method by setting different model parameter sparsities as target budgets during growing, and (3) *direct design*: our grown architectures re-initialized with random weights and re-trained. In most budget settings, our growing method outperforms direct design and uniform pruning, demon-

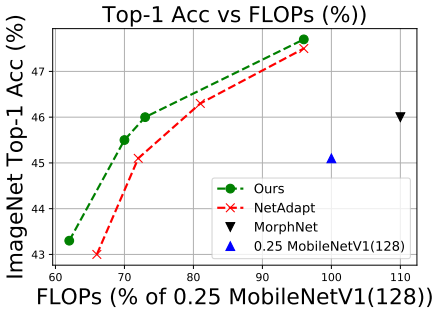


Figure 3: Performance/FLOPs trade-offs for pruned MobileNetV1 on ImageNet.

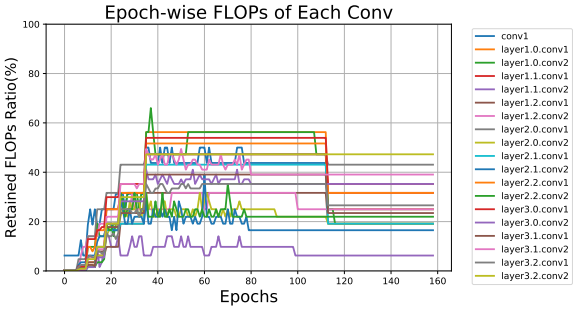


Figure 4: Epoch-wise training FLOPs for channel growing a ResNet-20.

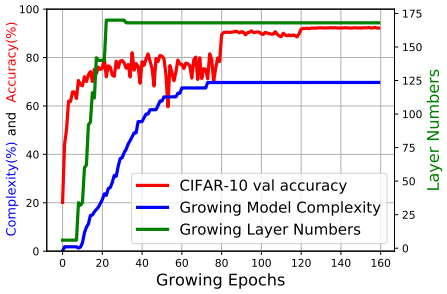


Figure 5: Tracking validation accuracy, complexity and layers for *Basic3ResNet* growing.

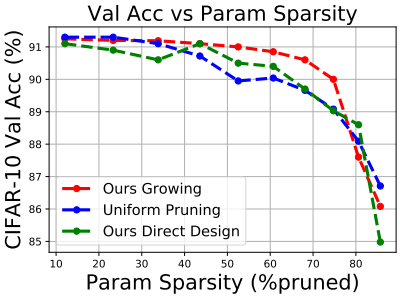


Figure 6: Pruned architectures obtained by ablated methods with different parameter sparsity.

strating higher parameter efficiency. Our method also appears to have positive effect in terms of regularization or optimization dynamics, which is lost if one attempts to directly train the final compact structure. Appendix A.9 investigates FLOPs-based budget targets.

Comparing with Random Baseline. In addition to the *uniform pruning* baseline in Figure 6, we also compare with a random sampling baseline to further separate the contribution of our configuration space and growing method, following the criterion in (Xie et al., 2019a; Li & Talwalkar, 2019; Yu et al., 2020; Radosavovic et al., 2019). Specifically, this random baseline replaces the procedure for sampling entries of $\boldsymbol{g}$ in Eq. 6. Instead of using sampling probabilities derived from the learned mask parameters $\boldsymbol{s}$, it samples with fixed probability. As shown in Table 5, our method consistently performs much better than this random baseline. These results, as well as the more sophisticated baselines in Figure 6, demonstrate the effectiveness of our growing and pruning approach.

Temperature Scheduler. We compare our structure-wise temperature control to a global one in channel growing experiments on CIFAR-10 using VGG-16, ResNet-20, and WideResNet-28-10. Table 1 results use our structure-wise scheduler. To achieve similar sparsity with the global scheduler, the corresponding models suffer accuracy drops of 1.4%, 0.6%, and 2.5%. With the global scheduler, optimization of mask variables stops early in training and the following epochs are equivalent to directly training a fixed compact network. This may force the network to be stuck with a suboptimal architecture. Appendix A.10 investigates learning rate and temperature schedule interactions.

5 Conclusion

In this paper, we propose a simple yet effective method to grow efficient deep networks via structured continuous sparsification, which decreases the computational cost not only of inference but also of training. The method is simple to implement and quick to execute, which aims at automating the network structure reallocation process under practical resource budgets. The applications to widely used deep networks on various tasks show that our method consistently generates models with better accuracy-efficiency trade-offs than competing methods, while achieving considerable training cost savings.

REFERENCES

Han Cai, Ligeng Zhu, and Song Han. Proxylessnas: Direct neural architecture search on target task and hardware. *CoRR*, abs/1812.00332, 2018.

Zhangjie Cao, Mingsheng Long, Jianmin Wang, and Philip S. Yu. Hashnet: Deep learning to hash by continuation. In *ICCV*, pp. 5609–5618. IEEE Computer Society, 2017. doi: 10.1109/ICCV.2017.598.

Liang-Chieh Chen, George Papandreou, Florian Schroff, and Hartwig Adam. Rethinking atrous convolution for semantic image segmentation. *arXiv:1706.05587*, 2017.

Kyunghyun Cho, Bart Van Merriënboer, Caglar Gulcehre, Dzmitry Bahdanau, Fethi Bougares, Holger Schwenk, and Yoshua Bengio. Learning phrase representations using RNN encoder-decoder for statistical machine translation. *arXiv preprint arXiv:1406.1078*, 2014.

François Chollet. Xception: Deep learning with depthwise separable convolutions. In *CVPR*, 2017.

Ekin Dogus Cubuk, Barret Zoph, Dandelion Mané, Vijay Vasudevan, and Quoc V. Le. Autoaugment: Learning augmentation policies from data. *CoRR*, abs/1805.09501, 2018.

Jia Deng, Wei Dong, Richard Socher, Li-Jia Li, Kai Li, and Li Fei-Fei. ImageNet: A large-scale hierarchical image database. In *CVPR*, 2009.

Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. Bert: Pre-training of deep bidirectional transformers for language understanding. *arXiv preprint arXiv:1810.04805*, 2018.

Mark Everingham, S. M. Ali Eslami, Luc Van Gool, Christopher K. I. Williams, John M. Winn, and Andrew Zisserman. The PASCAL visual object classes challenge: A retrospective. *IJCV*, 2015.

Jonathan Frankle and Michael Carbin. The lottery ticket hypothesis: Finding sparse, trainable neural networks. In *ICLR*, 2019.

Ross B. Girshick. Fast R-CNN. In *ICCV*, 2015.

Ariel Gordon, Elad Eban, Ofir Nachum, Bo Chen, Hao Wu, Tien-Ju Yang, and Edward Choi. MorphNet: Fast & simple resource-constrained structure learning of deep networks. In *CVPR*, 2018.

Priya Goyal, Piotr Dollár, Ross B. Girshick, Pieter Noordhuis, Lukasz Wesolowski, Aapo Kyrola, Andrew Tulloch, Yangqing Jia, and Kaiming He. Accurate, large minibatch SGD: training imagenet in 1 hour. *CoRR*, abs/1706.02677, 2017.

Sam Gross and Michael Wilber. Training and investigating residual nets. http://torch.ch/blog/2016/02/04/resnets.html, 2016.

Yiwen Guo, Anbang Yao, and Yurong Chen. Dynamic network surgery for efficient DNNs. In *NIPS*, 2016.

Song Han, Jeff Pool, John Tran, and William J. Dally. Learning both weights and connections for efficient neural networks. *NIPS*, 2015.

Song Han, Huizi Mao, and William J. Dally. Deep compression: Compressing deep neural network with pruning, trained quantization and huffman coding. *ICLR*, 2016.

Bharath Hariharan, Pablo Arbelaez, Lubomir D. Bourdev, Subhransu Maji, and Jitendra Malik. Semantic contours from inverse detectors. In *ICCV*, 2011.

Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *CVPR*, 2016.

Yang He, Guoliang Kang, Xuanyi Dong, Yanwei Fu, and Yi Yang. Soft filter pruning for accelerating deep convolutional neural networks. In *IJCAI*, 2018.

Geoffrey E. Hinton, Oriol Vinyals, and Jeffrey Dean. Distilling the knowledge in a neural network. *NIPS Deep Learning and Representation Learning Workshop*, 2015.

Sepp Hochreiter and Jurgen Schmidhuber. Long short-term memory. *Neural Computation*, 1997.

Andrew G. Howard, Menglong Zhu, Bo Chen, Dmitry Kalenichenko, Weijun Wang, Tobias Weyand, Marco Andreetto, and Hartwig Adam. Mobilenets: Efficient convolutional neural networks for mobile vision applications. *arXiv:1704.04861*, 2017.

Jie Hu, Li Shen, and Gang Sun. Squeeze-and-excitation networks. In *CVPR*, pp. 7132–7141. IEEE Computer Society, 2018. doi: 10.1109/CVPR.2018.00745.

Gao Huang, Yu Sun, Zhuang Liu, Daniel Sedra, and Kilian Q. Weinberger. Deep networks with stochastic depth. In *ECCV*, 2016.

Gao Huang, Zhuang Liu, Laurens van der Maaten, and Kilian Q. Weinberger. Densely connected convolutional networks. In *CVPR*, 2017.

Gao Huang, Shichen Liu, Laurens van der Maaten, and Kilian Q. Weinberger. CondenseNet: An efficient DenseNet using learned group convolutions. *CVPR*, 2018.

Itay Hubara, Matthieu Courbariaux, Daniel Soudry, Ran El-Yaniv, and Yoshua Bengio. Binarized neural networks. In *NIPS*, 2016.

Forrest N. Iandola, Matthew W. Moskewicz, Khalid Ashraf, Song Han, William J. Dally, and Kurt Keutzer. SqueezeNet: AlexNet-level accuracy with 50x fewer parameters and <1MB model size. *arXiv:1602.07360*, 2016.

Sergey Ioffe and Christian Szegedy. Batch normalization: Accelerating deep network training by reducing internal covariate shift. In *ICML*, 2015.

Eric Jang, Shixiang Gu, and Ben Poole. Categorical reparameterization with gumbel-softmax. In *ICLR*. OpenReview.net, 2017.

Alex Krizhevsky, Ilya Sutskever, and Geoffrey E Hinton. ImageNet classification with deep convolutional neural networks. In *NIPS*, 2012.

Alex Krizhevsky, Vinod Nair, and Geoffrey Hinton. The CIFAR-10 dataset. *http://www.cs.toronto.edu/~kriz/cifar.html*, 2014.

Carl Lemaire, Andrew Achkar, and Pierre-Marc Jodoin. Structured pruning of neural networks with budget-aware regularization. In *CVPR*, 2019.

Hao Li, Asim Kadav, Igor Durdanovic, Hanan Samet, and Hans Peter Graf. Pruning filters for efficient ConvNets. In *ICLR*, 2017.

Liam Li and Ameet Talwalkar. Random search and reproducibility for neural architecture search. In Amir Globerson and Ricardo Silva (eds.), *UAI*, pp. 129. AUAI Press, 2019.

Lucas Liebenwein, Cenk Baykal, Harry Lang, Dan Feldman, and Daniela Rus. Provable filter pruning for efficient neural networks. In *ICLR*, 2020.

Min Lin, Qiang Chen, and Shuicheng Yan. Network in network. *arXiv:1312.4400*, 2013.

Hanxiao Liu, Karen Simonyan, and Yiming Yang. DARTS: differentiable architecture search. *CoRR*, abs/1806.09055, 2018.

Hanxiao Liu, Karen Simonyan, and Yiming Yang. Darts: Differentiable architecture search. *ICLR*, 2019.

Wei Liu, Dragomir Anguelov, Dumitru Erhan, Christian Szegedy, Scott E. Reed, Cheng-Yang Fu, and Alexander C. Berg. SSD: single shot multibox detector. In *ECCV*, 2016.

Jonathan Long, Evan Shelhamer, and Trevor Darrell. Fully convolutional networks for semantic segmentation. In *CVPR*, 2015.

Christos Louizos, Max Welling, and Diederik P. Kingma. Learning sparse neural networks through l_0 regularization. *ICLR*, 2018.

Jian-Hao Luo, Jianxin Wu, and Weiyao Lin. ThiNet: A filter level pruning method for deep neural network compression. In *ICCV*, 2017.

Renqian Luo, Fei Tian, Tao Qin, Enhong Chen, and Tie-Yan Liu. Neural architecture optimization. In *NIPS*, 2018.

Mitchell P. Marcus, Beatrice Santorini, and Mary Ann Marcinkiewicz. Building a large annotated corpus of english: The penn treebank. *Computational Linguistics*, 1993.

Dmitry Molchanov, Arsenii Ashukha, and Dmitry P. Vetrov. Variational dropout sparsifies deep neural networks. In *ICML*, 2017.

Hieu Pham, Melody Y Guan, Barret Zoph, Quoc V Le, and Jeff Dean. Efficient neural architecture search via parameter sharing. *arXiv preprint arXiv:1802.03268*, 2018.

Ilija Radosavovic, Justin Johnson, Saining Xie, Wan-Yen Lo, and Piotr Dollár. On network design spaces for visual recognition. In *ICCV*, pp. 1882–1890. IEEE, 2019. doi: 10.1109/ICCV.2019.00197.

Mohammad Rastegari, Vicente Ordonez, Joseph Redmon, and Ali Farhadi. XNOR-Net: Imagenet classification using binary convolutional neural networks. In *ECCV*, 2016.

Esteban Real, Alok Aggarwal, Yanping Huang, and Quoc V Le. Regularized evolution for image classifier architecture search. *arXiv preprint arXiv:1802.01548*, 2018.

Pedro Savarese and Michael Maire. Learning implicitly recurrent CNNs through parameter sharing. In *ICLR*, 2019.

Pedro Savarese, Hugo Silva, and Michael Maire. Winning the lottery with continuous sparsification. *arXiv:1912.04427*, 2019.

Laurent Sifre and PS Mallat. *Rigid-motion scattering for image classification*. PhD thesis, Ecole Polytechnique, CMAP, 2014.

Karen Simonyan and Andrew Zisserman. Very deep convolutional networks for large-scale image recognition. *ICLR*, 2015.

Mingxing Tan and Quoc V. Le. Efficientnet: Rethinking model scaling for convolutional neural networks. In Kamalika Chaudhuri and Ruslan Salakhutdinov (eds.), *ICML*, volume 97 of *Proceedings of Machine Learning Research*, pp. 6105–6114. PMLR, 2019.

Mingxing Tan, Bo Chen, Ruoming Pang, Vijay Vasudevan, and Quoc V Le. Mnasnet: Platform-aware neural architecture search for mobile. *arXiv:1807.11626*, 2018.

Mingxing Tan, Bo Chen, Ruoming Pang, Vijay Vasudevan, Mark Sandler, Andrew Howard, and Quoc V Le. Mnasnet: Platform-aware neural architecture search for mobile. In *CVPR*, pp. 2820–2828, 2019.

Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Łukasz Kaiser, and Illia Polosukhin. Attention is all you need. In *Advances in neural information processing systems*, pp. 5998–6008, 2017.

Tao Wei, Changhu Wang, Yong Rui, and Chang Wen Chen. Network morphism. In Maria-Florina Balcan and Kilian Q. Weinberger (eds.), *ICML*, volume 48 of *JMLR Workshop and Conference Proceedings*, pp. 564–572. JMLR.org, 2016.

Wei Wen, Yuxiong He, Samyam Rajbhandari, Minjia Zhang, Wenhan Wang, Fang Liu, Bin Hu, Yiran Chen, and Hai Li. Learning intrinsic sparse structures within long short-term memory. In *ICLR*, 2018.

Wei Wen, Feng Yan, Yiran Chen, and Hai Li. Autogrow: Automatic layer growing in deep convolutional networks. In Rajesh Gupta, Yan Liu, Jiliang Tang, and B. Aditya Prakash (eds.), *KDD*, pp. 833–841. ACM, 2020.

Mitchell Wortsman, Ali Farhadi, and Mohammad Rastegari. Discovering neural wirings. In Hanna M. Wallach, Hugo Larochelle, Alina Beygelzimer, Florence d'Alché-Buc, Emily B. Fox, and Roman Garnett (eds.), *NeurIPS*, pp. 2680–2690, 2019.

Bichen Wu, Xiaoliang Dai, Peizhao Zhang, Yanghan Wang, Fei Sun, Yiming Wu, Yuandong Tian, Peter Vajda, Yangqing Jia, and Kurt Keutzer. Fbnet: Hardware-aware efficient convnet design via differentiable neural architecture search. In *CVPR*, pp. 10734–10742, 2019.

Lingxi Xie and Alan L Yuille. Genetic cnn. In *ICCV*, pp. 1388–1397, 2017.

Saining Xie, Alexander Kirillov, Ross B. Girshick, and Kaiming He. Exploring randomly wired neural networks for image recognition. In *ICCV*, pp. 1284–1293. IEEE, 2019a. doi: 10.1109/ICCV.2019.00137.

Sirui Xie, Hehui Zheng, Chunxiao Liu, and Liang Lin. SNAS: stochastic neural architecture search. In *ICLR*. OpenReview.net, 2019b.

Zhenda Xie, Zheng Zhang, Xizhou Zhu, Gao Huang, and Stephen Lin. Spatially adaptive inference with stochastic feature sampling and interpolation. *CoRR*, abs/2003.08866, 2020.

Tien-Ju Yang, Andrew G. Howard, Bo Chen, Xiao Zhang, Alec Go, Mark Sandler, Vivienne Sze, and Hartwig Adam. NetAdapt: Platform-aware neural network adaptation for mobile applications. In *ECCV*, 2018.

Kaicheng Yu, Christian Sciuto, Martin Jaggi, Claudiu Musat, and Mathieu Salzmann. Evaluating the search phase of neural architecture search. In *ICLR*. OpenReview.net, 2020.

Sergey Zagoruyko and Nikos Komodakis. Wide residual networks. In *BMVC*, 2016.

Wojciech Zaremba, Ilya Sutskever, and Oriol Vinyals. Recurrent neural network regularization. *arXiv:1409.2329*, 2014.

Xiangyu Zhang, Xinyu Zhou, Mengxiao Lin, and Jian Sun. ShuffleNet: An extremely efficient convolutional neural network for mobile devices. *CVPR*, 2018.

Barret Zoph and Quoc V Le. Neural architecture search with reinforcement learning. *arXiv:1611.01578*, 2016.

Barret Zoph, Vijay Vasudevan, Jonathon Shlens, and Quoc V Le. Learning transferable architectures for scalable image recognition. *CVPR*, 2018.

A APPENDIX

A.1 MORE DETAILED ANALYSIS FOR BUDGET-AWARE GROWING

Conducting grid search on trade-off parameters λ_1 and λ_2 is prohibitively laborious and time-consuming. For example, to grow an efficient network on CIFAR-10, one needs to repeat many times of 160-epochs training and then pick the best model from all grown candidates. To avoid this tedious iterative process, instead of using constants λ_1 and λ_2, we dynamically update λ_1 and λ_2 in our one-shot budget-aware growing optimization.

Here we discuss about how the budget-aware dynamic growing works in our method. Without loss of generality, we derive the m_c's SGD updating rule for ℓ_0 regularization term in Eq. 3 as:

$$m_c \leftarrow m_c - \eta \lambda_1^{base} \Delta u \frac{\delta \ell}{\delta m_c} - \eta \mu \lambda_1^{base} \Delta u m_c \tag{8}$$

where η is learning rate and μ is weight decay. At the beginning of growing epochs when the architecture is very over-sparsified, Δu and $\lambda_1^{base} \Delta u$ are negative values. Then m_c updating is along the **opposite** directions of standard ℓ_0 regularization term's gradients encouraging m_c's sparsification. As a result, some zero-valued m_c will be activated and the model complexity is strongly grown to acquire enough capacity to be well trained. Then growing become gradually weaker when the network sparsity approaches the budget (Δu to zero). Note that if the architecture is over-parameterized, Δu and $\lambda_1^{base} \Delta u$ become positive and the SGD updating rule is the same as that of normal ℓ_0 regularization. As such, our budget-aware growing can automatically and dynamically adapting the architecture complexity not only based on the task loss L_E but also the practical budgets requirements in the one-shot training process.

We also note that NAS methods usually use the validation accuracy as a target during their architecture optimization phase, which may require some prior knowledge of validation accuracy on a given dataset. Our growing choose sparsity budget instead of accuracy as target because (1) during our growing, validation accuracy is influenced not only by architectures but also model weights. Directly using Δacc may lead to sub-optimal architecture optimization. (2) Budget target is more practical and easier to set according to target devices for deployment.

A.2 DETAILS OF EVALUATION DATASETS

Evaluation is conducted on various tasks to demonstrate the effectiveness of our proposed method. For image classification, we use CIFAR-10 (Krizhevsky et al., 2014) and ImageNet (Deng et al., 2009): CIFAR-10 consists of 60,000 images of 10 classes, with 6,000 images per class. The train and test sets contain 50,000 and 10,000 images respectively. ImageNet is a large dataset for visual recognition which contains over 1.2M images in the training set and 50K images in the validation set covering 1,000 categories. For semantic segmentation, we use the PASCAL VOC 2012 (Everingham et al., 2015) benchmark which contains 20 foreground object classes and one background class. The original dataset contains 1,464 (train), 1,449 (val), and 1,456 (test) pixel-level labeled images for training, validation, and testing, respectively. The dataset is augmented by the extra annotations provided by (Hariharan et al., 2011), resulting in 10,582 training images. For language modeling, we use the word level Penn Treeban (PTB) dataset (Marcus et al., 1993) which consists of 929k training words, 73k validation words and 82k test words with 10,000 unique words in its vocabulary.

A.3 UNPRUNED BASELINE MODELS

For CIFAR-10, we use VGG-16 (Simonyan & Zisserman, 2015) with BatchNorm (Ioffe & Szegedy, 2015), ResNet-20 (He et al., 2016) and WideResNet-28-10 (Zagoruyko & Komodakis, 2016) as baselines. We adopt a standard data augmentation scheme (shifting/mirroring) following (Lin et al., 2013; Huang et al., 2016), and normalize the input data with channel means and standard deviations. Note that we use the CIFAR version of ResNet-20 [1], VGG-16 [2], and WideResNet-28-10 [3]. VGG-16, ResNet-20, and WideResNet-28-10 are trained for 160, 160 and 200 epochs with a batch size of 128

[1] https://github.com/akamaster/pytorch_resnet_cifar10/blob/master/resnet.py
[2] https://github.com/kuangliu/pytorch-cifar/blob/master/models/vgg.py
[3] https://github.com/meliketoy/wide-resnet.pytorch/blob/master/networks/wide_resnet.py

and initial learning rate of 0.1. For VGG-16 and ResNet-20 we divide learning rate by 10 at epochs 80 and 120 and set the weights decay and momentum as 10^{-4} and 0.9. For WideResNet-28-10, the learning rate is divided by 5 at epochs 60, 120 and 160; the weight decay and momentum are set to 5×10^{-4} and 0.9. For ImageNet, we train the baseline ResNet-50 and MobileNetV1 model following the respective papers. We adopt the same data augmentation scheme as in (Gross & Wilber, 2016) and report top-1 validation accuracy. For semantic segmentation, the performance is measured in terms of pixel intersection-over-union (IOU) averaged across the 21 classes (mIOU). We use Deeplab-v3-ResNet-101[4] (Chen et al., 2017) as the baseline model following the training details in (Chen et al., 2017). For language modeling, we use vanilla two-layer stacked LSTM (Zaremba et al., 2014) as a baseline. The dropout keep ratio is 0.35 for the baseline model. The vocabulary size, embedding size, and hidden size of the stacked LSTMs are set as 10,000, 1,500, and 1,500, respectively, which is consistent with the settings in (Zaremba et al., 2014).

A.4 MobileNetV1 Channel Growing on ImageNet

To further validate the effectiveness of the proposed method on compact networks, we grow the filters of MobileNetV1 on ImageNet and compare the performance of our method to the results reported directly in the respective papers, as shown in Table 6. In MobileNetV1 experiments, following the same setting with Netadapt (Yang et al., 2018), we apply our method on both (1) small setting: growing MobileNetV1(128) with 0.5 multiplier while setting the original model's multiplier as 0.25 for comparison and (2) large setting: growing standard MobileNetV1(224) while setting the original model's multiplier as 0.75 for comparison. Note that MobileNetV1 is one of the most compact networks, and thus is more challenging to simplify than other larger networks. Our lower-cost growing method can still generate a sparser MobileNetV1 model compared with competing methods.

Table 6: Overview of the pruning performance of each algorithm on MobileNetV1 ImageNet.

Model	Method	Top-1 Val Acc(%)	FLOPs(%)	Train-Cost Savings(×)
MobileNet V1(128)	Original(25%)	45.1 (+0)	100	1(×)
	MorphNet	46.0 (+0.9)	110	0.9(×)
	Netadapt	**46.3 (+1.2)**	81	1.1(×)
	Ours	46.0 (+0.9)	**73**	**1.7**(×)
MobileNet V1(224)	Original(75%)	68.8 (+0)	100	1(×)
	Netadapt	69.1 (+0.3)	87	1.2(×)
	Ours	**69.3 (+0.5)**	**83**	**1.5**(×)

A.5 Deeplab-v3-ResNet-101 on PASCAL VOC 2012

We also test the effectiveness of our proposed method on the semantic segmentation task by growing the Deeplab-v3-ResNet-101 model's filter numbers from scratch directly on the PASCAL VOC 2012 dataset. We apply our method to both the ResNet-101 backbone and ASPP module. Compared to the baseline, the final generated network reduces the FLOPs by 58.5% and the parameters amount by 49.8% while approximately maintaining mIoU (76.5% to 76.4%). See Table 7.

Table 7: Results on the PASCAL VOC dataset.

Model	Method	mIOU	Params(M)	FLOPs(%)	Train-Cost Savings(×)
Deeplab -v3- ResNet101	Original	76.5 (+0)	58.0 (100%)	100	1(×)
	L1-Pruning	75.1 (-1.4)	45.7 (78.8%)	62.5	1.3(×)
	Ours	**76.4 (-0.1)**	**29.1 (50.2%)**	**41.5**	**2.3**(×)

[4]https://github.com/chenxi116/DeepLabv3.pytorch

A.6 EXTENSION TO RECURRENT CELLS ON PTB DATASET

Without loss of generality, we focus on LSTMs (Hochreiter & Schmidhuber, 1997) with l_h hidden neurons, a common variant[5] of RNNs that learns long-term dependencies:

$$
\begin{aligned}
f_t &= \sigma_g((W_f \odot (\mathbf{e} m_c^T))x_t + (U_f \odot (m_c m_c^T))h_{t-1} + b_f) \\
i_t &= \sigma_g((W_i \odot (\mathbf{e} m_c^T))x_t + (U_i \odot (m_c m_c^T))h_{t-1} + b_i) \\
o_t &= \sigma_g((W_o \odot (\mathbf{e} m_c^T))x_t + (U_o \odot (m_c m_c^T))h_{t-1} + b_o) \\
\tilde{c}_t &= \sigma_h((W_c \odot (\mathbf{e} m_c^T))x_t + (U_c \odot (m_c m_c^T))h_{t-1} + b_c) \\
c_t = f_t \odot c_{t-1} + i_t \odot \tilde{c}_t, &\quad h_t = o_t \odot \sigma_h(c_t) \quad s.t. \quad m_c \in \{0,1\}^{l_h}, \mathbf{e} = 1^{l_h} ,
\end{aligned} \tag{9}
$$

where σ_g is the sigmoid function, $\odot$ denotes element-wise multiplication and σ_h is the hyperbolic tangent function. x_t denotes the input vector at the time-step t, h_t denotes the current hidden state, and c_t denotes the long-term memory cell state. W_f, W_i, W_o, W_c denote the input-to-hidden weight matrices and U_f, U_i, U_o, U_c denote the hidden-to-hidden weight matrices. m_c is binary indicator and shared across all the gates to control the sparsity of hidden neurons.

We compare our proposed method with ISS based on vanilla two-layer stacked LSTM. As shown in Table 8, our method finds more compact model structure using lower training costs, while achieving similar perplexity on both validation and test sets. These improvements may be due to the fact that our method dynamically grows and prunes the hidden neurons from very simple status towards a better trade-off between model complexity and performance than that of ISS, which simply uses the group lasso to penalize the norms of all groups collectively for compactness.

Table 8: Results on the PTB dataset.

Method	Perplexity (val,test)	Final Structure	Weight(M)	FLOPs(%)	Train-Cost Savings($\times$)
Original	(82.57, 78.57)	(1500, 1500)	66M (100%)	100	1($\times$)
ISS	(82.59, **78.65**)	(373, 315)	21.8M (33.1%)	13.4	3.8($\times$)
Ours	(**82.46**, 78.68)	**(310, 275)**	**20.6M (31.2%)**	**11.9**	**5.1**($\times$)

A.7 VARIANTS OF INITIAL SEED ARCHITECTURE

In Table 9, we make a detailed comparison among initial seed architectures variants of ours and AutoGrow (Wen et al., 2020). For both ours and AutoGrow, "Basic" and "Bottleneck" refers to ResNets with standard basic and bottleneck residual blocks while "PlainLayers" refers to stacked of convolutional, batch normalization and ReLU layer combinations. Similar with standard ResNets, for variants of the seed architectures, we adopt 3-stage for CIFAR-10 while 4-stage for ImageNet. PlainNets can be obtained by simply removing shortcuts from these ResNet seed variants with same stage numbers. For each stage, we start from only one growing unit, within which initial filter numbers are also initialized as 1 for channel growing.

A.8 TRACK OF ANY-TIME SPARSIFICATION DURING CHANNEL GROWING

Figure 7 and Figure 8 shows the dynamics of train-time growing channel ratios of ResNet-20 and VGG-16 on CIFAR-10, respectively. To better analyze the growing patterns, we visualize the channel dynamics grouped by stages in Figure 9 for ResNet-20 and Figure 10 for VGG-16, respectively. Note that, for VGG-16, we divide it into 5 stages based on the pooling layer positions and normalize channel ratios by 0.5 for better visualization. We see that our method grows more channels of earlier layers within each stage of ResNet-20. Also, the final channel sparsity of ResNet-20 is more uniform due to the residual connections.

Table 9: A detailed comparison among seed architectures variants of ours and AutoGrow (Wen et al., 2020). In growing units term, "Basic" and "Bottleneck" refers to ResNets with standard basic and bottleneck residual blocks while "PlainLayers" refers to standard convolutional layer, BN and ReLu layer combinations in VGG-like networks without shortcuts.

Families	Variants	Methods	Channel Growing	Growing Units	Stages	Shortcuts
ResNet	*Basic3ResNet*	Ours	✓	Basic	3	✓
		AutoGrow	✗			✓
	Bottleneck4ResNet	Ours	✓	Bottleneck	4	✓
		AutoGrow	✗			✓
VGG-like	*Plain3Net*	Ours	✓	PlainLayers	3	✗
		AutoGrow	✗			✗
	Plain4Net	Ours	✓	PlainLayers	4	✗
		AutoGrow	✗			✗

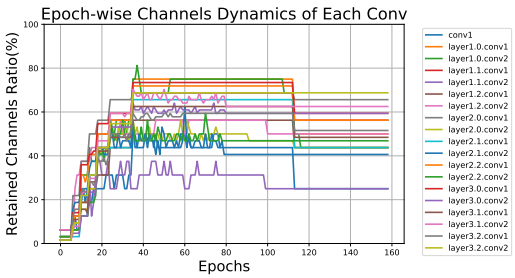


Figure 7: Epoch-wise retained channel ratio dynamics for each layer in ResNet-20.

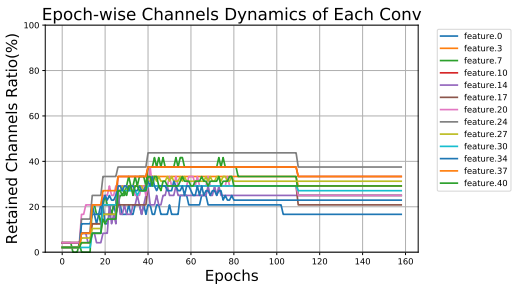


Figure 8: Epoch-wise retained channel ratio dynamics for each layer in VGG-16.

A.9 FLOPs-BASED BUDGET-AWARE GROWING

We also investigate the effectiveness of setting FLOPs target for budget-aware growing in Figure 11. We observe similar trends among *uniform pruning*, *ours growing* and *ours direct design*: in most FLOPs budget settings, our growing method outperforms direct design and uniform pruning. We also observe that when setting extreme sparse FLOPs target (e.g 85%), our methods achieve even lower accuracy than other two variants. The reason is that our channel growing is forced to only grow architectures from $\sim 99\%$ sparsity up to $\sim 85\%$ FLOPs and $\sim 90\%$ parameters sparsity, during which models cannot acquire enough capacity to be well trained.

A.10 INTERACTIONS BETWEEN LEARNING RATE AND TEMPERATURE SCHEDULERS

There're two factors influencing the growing optimization speed in our method: temperature and learning rate, which are hyperparameters controlled by their respective schedulers. We first visualize the structure-wise separate temperature dynamics in Figure 12 by averaging temperatures per layer during resnet-20 channel growing on CIFAR-10. We see that temperatures are growing with different rates for channels. Usually, low learning rate and high temperature in late training epochs make the network growing optimization become very stable. In Figure 13, we deliberately decaying γ in the temperature scheduler along with learning rate decaying epochs to force growing until the end. As shown in Figure 14, our method still adapting some layers even at the last epoch. We also find that such instability will degrade the performance since some newly grown filters may not get enough time to be well trained.

[5]The proposed configuration space can be readily applied to the compression of GRUs (Cho et al., 2014) and vanilla RNNs.

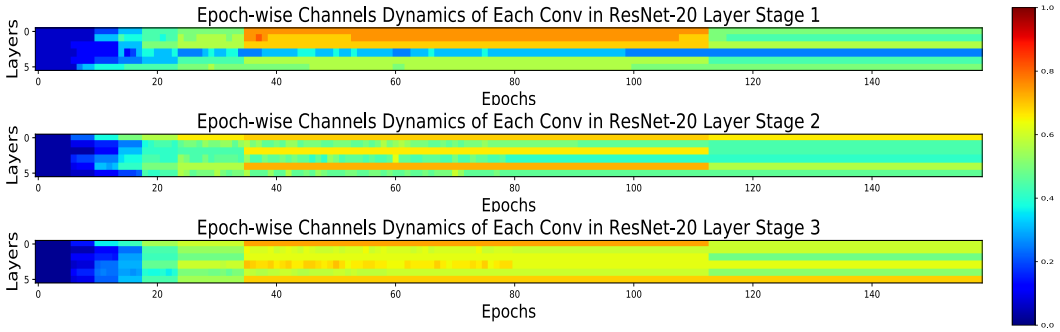


Figure 9: Visualization of retained channel ratio dynamics for each stage in ResNet-20.

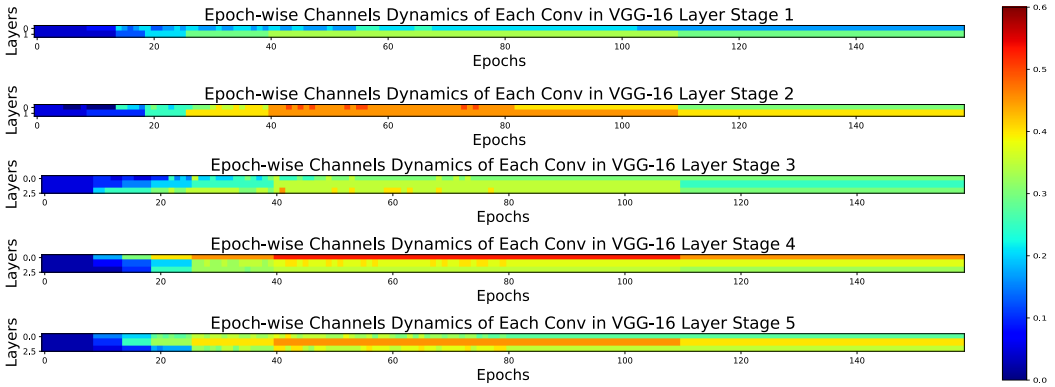


Figure 10: Visualization of retained channel ratio dynamics for each stage in VGG-16.

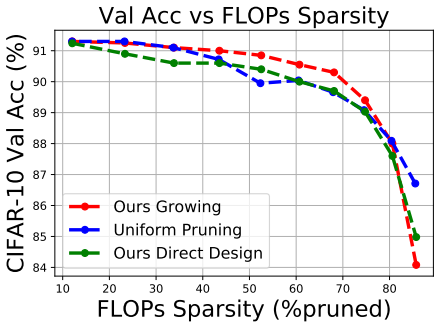


Figure 11: Pruned architectures obtained by ablated methods with different FLOPs sparsity.

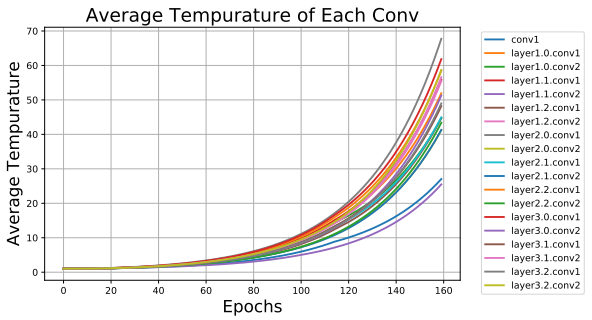


Figure 12: Structure-wise separate temperature dynamics in channel growing.

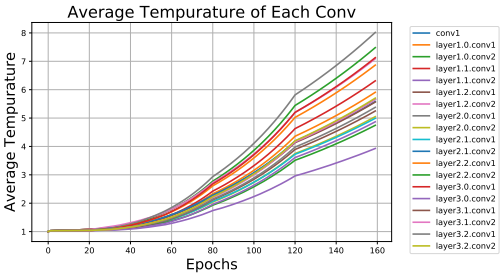


Figure 13: Structure-wise separate decayed temperature dynamics in channel growing.

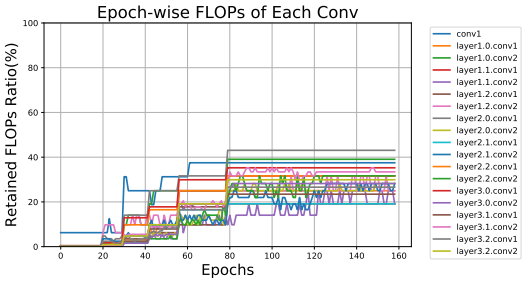


Figure 14: Track of epoch-wise train-time FLOPs for channel growing in ResNet-20.