ShiftAddNAS: Hardware-Inspired Search for More Accurate and Efficient Neural Networks

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Abstract

Neural networks (NNs) with intensive multiplications (e.g., convolutions and transformers) are capable yet power hungry, impeding their more extensive deployment into resource-constrained devices. As such, multiplication-free networks, which follow a common practice in energy-efficient hardware implementation to parameterize NNs with more efficient operators (e.g., bitwise shifts and additions), have gained growing attention. However, multiplication-free networks usually under-perform their vanilla counterparts in terms of the achieved accuracy. To this end, this work advocates hybrid NNs that consist of both powerful yet costly multiplications and efficient yet less powerful operators for marrying the best of both worlds, and proposes ShiftAddNAS, which can automatically search for more accurate and more efficient NNs. Our ShiftAddNAS highlights two enablers. Specifically, it integrates (1) the first hybrid search space that incorporates both multiplication-based and multiplication-free operators for facilitating the development of both accurate and efficient hybrid NNs; and (2) a novel weight sharing strategy that enables effective weight sharing among different operators that follow heterogeneous distributions (e.g., Gaussian for convolutions vs. Laplacian for add operators) and simultaneously leads to a largely reduced supernet size and much better searched networks. Extensive experiments and ablation studies on various models, datasets, and tasks consistently validate the efficacy of ShiftAddNAS, e.g., achieving up to a +7.7% higher accuracy or a +4.9 better BLEU score compared to state-of-the-art NN, while leading to up to 93% or 69%

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1. Introduction

The unprecedented performance achieved by neural networks (NNs), e.g., convolutional neural networks (CNNs) and Transformers, requires intensive multiplications and thus prohibitive training and inference costs, contradicting the explosive demand for embedding various intelligent functionalities into pervasive resource-constrained edge devices. In response, multiplication-free networks have been proposed to alleviate the prohibitive resource requirements by replacing the costly multiplications with lower-cost operators for boosting hardware efficiency. For example, AdderNet (Chen et al., 2020) utilizes mere additions to design NNs; and ShiftAddNet (You et al., 2020a) follows a commonly used hardware practice to re-parameterize NNs with both bitwise shifts and additions. Despite their promising performance in hardware efficiency, multiplication-free NNs in general under-perform their CNN and Transformer counterparts in terms of task accuracy for both computer vision (CV) and natural language processing (NLP) applications.

To marry the best of both worlds, we advocate hybrid multiplication-reduced network architectures that integrate both multiplication-based operators (e.g., vanilla convolution (Krizhevsky et al., 2012) and attention (Vaswani et al., 2017)) and multiplication-free operators (e.g., shift and add (You et al., 2020a)) to simultaneously boost task accuracy and efficiency. Thanks to the amazing success of neural architecture search (NAS) in automating the process of designing state-of-the-art (SOTA) NNs, it is natural to consider NAS as the design engine of the aforementioned hybrid NNs for various applications and tasks, each often requiring a different performance-efficiency trade-off. However, there still exist a few challenges in leveraging NAS to design the hybrid NNs. First, existing NAS methods mostly consider the search for either efficient CNNs (Wan et al., 2020), Transformers (Chen et al., 2021b), or hybrid CNN-Transformers (Ding et al., 2021; Li et al., 2021), and there still is a lack of a seminal work that searches for multiplication-reduced hybrid networks, especially for the
hardware-inspired networks that incorporate both bitwise shifts and additions. Second, a hybrid search space could make it more challenging to achieve effective NAS and further aggravate the search burden, due to the enlarged search space imposed by the newly introduced multiplication-free operators. It is worth noting that existing weight sharing strategies of NAS cannot directly be applied to the target hybrid search space, because weights of different operators follow heterogeneous distributions, leading to a dilemma of either inefficient search or inconsistent architecture ranking. Specifically, weights in convolutional and adder layers follow Gaussian and Laplacian distributions, respectively, as also highlighted by (Chen et al., 2020; Xu et al., 2020). As such, forcing weight sharing among heterogeneous operators could hurt the capacity and thus the achieved accuracy of the resulting NNs, while treating them separately could explode the search space and make it more difficult to achieve effective NAS, i.e., the dilemma mentioned above.

To tackle the aforementioned challenges towards more accurate and efficient NNs, this work makes the following contributions:

1. We propose a generic NAS framework dubbed ShiftAddNAS, which for the first time can automatically search for efficient hybrid NNs with both superior accuracy and efficiency. Our ShiftAddNAS integrates a hybrid hardware-inspired search space that incorporates both multiplication-based operators (e.g., convolution and attention) and multiplication-free operators (e.g., shift and add), and can serve as a play-and-plug module to be applied on top of SOTA NAS works for further boosting their achievable accuracy and efficiency.

2. We develop a new weight sharing strategy for effective search with hybrid search spaces, which only incurs a negligible overhead when searching for hybrid operators with heterogeneous (e.g., Gaussian vs. Laplacian) weight distributions as compared to the vanilla NAS with merely multiplication-based operators, alleviating the dilemma mentioned above regarding either inefficient search or inconsistent architecture ranking.

3. We conduct extensive experiments and ablation studies to validate the effectiveness of ShiftAddNAS against SOTA works. Results on multiple benchmarks demonstrate the superior accuracy and hardware efficiency of its searched NNs as compared to both (1) manually designed multiplication-free networks, CNNs, Transformers, and hybrid CNN-Transformers, and (2) SOTA NAS works, on both CV and NLP tasks.

2. Related Works

Multiplication-free NNs. Many efficient NNs aim to reduce their intensive multiplications that dominate the time/energy costs. One important trend is to replace the multiplications with lower-cost operators: BNNs (Courbariaux et al., 2016; Juefei-Xu et al., 2017) binarize both the weights and activations and reduce multiplications to merely sign flips at non-negligible accuracy drops; Adder-Nets (Chen et al., 2020; Xu et al., 2020; Wang et al., 2021b) fully replace the multiplications with lower-cost additions and further develop an effective backpropagation scheme for efficient AdderNet training; Shift-based NNs leverage either spatial shift (Wu et al., 2018) or bit-wise shift operations, e.g., DeepShift (Elhoushi et al., 2021), to reduce the amount of multiplications; and ShiftAddNet (You et al., 2020a) draws inspirations from efficient hardware designs to reparamatize NNs with mere bitwise shifts and additions. While multiplication-free NNs under-perform their vanilla NN counterparts in terms of achieved accuracy, ShiftAddNAS aims to automatically search for multiplication-reduced NNs that incorporate both multiplication-based and multiplication-free operators for marrying the best of both worlds, i.e., boosted accuracy and efficiency.

Neural architecture search. NAS has achieved an amazing success in automating the design of efficient NN architectures. For searching for CNNs, early works (Tan & Le, 2019; Tan et al., 2019; Howard et al., 2019) adopt reinforcement learning based methods that require a prohibitive search time and computing resources, while recent works (Liu et al., 2018; Wu et al., 2019a; Wan et al., 2020; Yang et al., 2021) utilize differentiable search to greatly improve the search efficiency. More recently, some works adopt one-shot NAS (Guo et al., 2020; Cai et al., 2019; Yu et al., 2020; Wang et al., 2021a) to decouple the architecture search from supernet training and then evaluate the performance of sub-networks whose weights are directly inherited from the pretrained supernet. For searching better Transformers, recently emerging works (Wang et al., 2020a; Su et al., 2021; Chen et al., 2021a) take one-shot NAS and an evolutionary algorithm to obtain optimal Transformer architectures for both NLP and CV tasks. Additionally, BossNAS (Li et al., 2021) and HR-NAS (Ding et al., 2021) further search for hybrid CNN-Transformer architectures.

Nevertheless, little effort has been made to explore NAS methods especially their search strategies for multiplication-reduced NNs. Furthermore, it is not clear whether existing efficient NAS methods are applicable to search for such multiplication-reduced NNs. As such, it is highly desirable to develop NAS methods, e.g., ShiftAddNAS, dedicated for hardware-inspired multiplication-reduced NNs to increase achievable accuracy and efficiency.

Transformers. Transformers (Vaswani et al., 2017) were first proposed for NLP tasks, which have inspired many interesting works. Some advance Transformer architecture by improving the attention mechanism (Chen et al., 2018), training deeper Transformers (Wang et al., 2019), and replacing the attention with convolutional modules...
(Wu et al., 2019b); and others strive to reduce Transformers’ computational complexity by adopting sparse attention mechanisms (Zaheer et al., 2020), low-rank approximation (Wang et al., 2020b), or compression techniques (Wu et al., 2020). Recently, there has been a growing interest in developing Transformers for CV tasks. Vision Transformer (ViT) (Dosovitskiy et al., 2021) for the first time successfully applies pure Transformers to image classification and achieves SOTA task accuracy, which yet relies on pretraining on giant datasets. Following works including DeiT (Touvron et al., 2021), the authors in T2T-ViT (Yuan et al., 2021) develop new training recipes and tokenization schemes, for achieving comparable accuracy without the necessity of costly pretraining; and another trend is to incorporate CNN modules into Transformer architectures for better accuracy and efficiency tradeoffs (Wu et al., 2021; Graham et al., 2021). In contrast, we advocate hybrid multiplication-reduced NNs and develop an automated search framework that can automatically search for such hardware inspired hybrid models.

3. The Proposed ShiftAddNAS Framework

In this section, we first introduce the hybrid search space from both algorithmic and hardware cost perspectives, providing high-level background and justification for motivating ShiftAddNAS; Sec. 3.2 elaborates the one-shot search method of ShiftAddNAS by first analyzing the dilemma of either inefficient search or inconsistent architecture ranking and then introducing the proposed novel heterogeneous weight sharing strategy tackling the aforementioned dilemma.

3.1. ShiftAddNAS: Hybrid Search Space

**Candidate blocks.** The first step of developing ShiftAddNAS is to construct a hybrid search space incorporating suitable building blocks that exhibit various performance-efficiency trade-offs. Specifically, we hypothesize that integrating both multiplication-based and multiplication-free blocks into the search space could lead to both boosted accuracy and efficiency, and consider blocks from two trends of designing NNs: (1) capable NNs, e.g., vanilla CNNs and Transformers, leverage either convolutions (Conv) or multi-head self-attentions (Attn) that comprise of intensive multiplications to capture local or global correlations, achieving a SOTA accuracy in both CV and NLP tasks; and (2) efficient multiplication-free NNs, e.g., ShiftAddNet, draw inspirations from hardware design practices to incorporate two efficient and complementary blocks, i.e., coarse-grained Shift and fine-grained Add, for favoring hardware efficiency, while maintaining a decent accuracy. While our constructed general hybrid search space for both NLP and CV tasks are shown in Fig. 2, we next analyze the building blocks from both algorithmic and hardware costs perspectives.

**Attn** is a core component of Transformers (Vaswani et al., 2017), which consists of a number of heads H with each capturing different global-context information by measuring pairwise correlations among tokens as defined below:

\[ O_{Attn} = Concat(H_1, \ldots, H_H) \cdot W^O, \]

\[ H_i = Softmax\left(\frac{QW_i^Q \cdot (KW_i^K)^T}{\sqrt{d_k}}\right) \cdot V W_i^V, \]  

where \( h \) denotes the number of heads, \( Q, K, V \in \mathbb{R}^{n \times d} \) are the query, key, and value embeddings of hidden dimension \( d \) obtained by linearly projecting the input sequence of length \( n \). In this way, the Attn block first computes dot-products between key-query pairs, scales to stabilize the training, uses \( \text{Softmax} \) to normalize the resulting attention scores, and then computes a weighted sum of the value embeddings corresponding to different inputs. Finally, the results from all heads are concatenated and further projected with a weight matrix \( W^O \in \mathbb{R}^{k \times d} \) to generate the outputs.

**Conv** is a key operator of CNNs, which models the local-context information of high-dimensional inputs such as images through sliding kernel weights \( W \) on top of inputs \( X \) to measure their similarity (Gu et al., 2018), as defined in Eq. (2). Its translation invariant and weight sharing ability leads to various SOTA CNNs (He et al., 2016) or hybrid CNN-Transformer models (Xiao et al., 2021). However, the computational complexities of CNNs can be prohibitive due to their intensive multiplications. For example, one forward pass of ResNet-50 (He et al., 2016) requires 4G floating point multiplications.

\[ O_{Conv} = \sum X^T \ast W \]  

**Shift** is a well-known efficient hardware primitive, motivating the recent development of shift-based efficient NNs. For example, DeepShift (Elhoushi et al., 2021) parametrizes NNs with bitwise shifts and sign flips, as formulated in Eq. (3), with \( W = S \cdot 2^P \) denoting weights in the shift blocks, where \( S \in \{-1, 0, 1\} \) are sign flip operators and the power-of-two parameter for \( P \) represents the bitwise shifts. However, NNs built with shift blocks and quantized weights are observed to be inferior to multiplication-based NNs in terms of expressiveness (accuracy) as validated in (You et al., 2020a).

\[ O_{Shift} = \sum X^T \ast (S \cdot 2^P) \]  

**Add** is another efficient hardware primitive which motivates recent works (Chen et al., 2020; Wang et al., 2021b; Song et al., 2021) to design efficient NNs using merely additions to measure the similarity between kernel weights \( W \) and inputs \( X \), as shown in Eq. (4). Such add-based NNs (Chen et al., 2020; Xu et al., 2020) in general have a better expressive capacity than their shift-based counterparts. For example, AdderNets (Chen et al., 2020) achieve
a 1.37% higher accuracy than DeepShift under similar or even lower FLOPs on ResNet-18 with the ImageNet dataset. However, add-based operators (i.e., repeated additions) are not parameter-efficient as compared to bitwise shift operations (You et al., 2020a). While NNs combining shift and add achieve a boosted accuracy, efficiency, and robustness than NNs using merely either of them, their accuracy still compares unfavorably in contrast to vanilla CNNs or Transformers.

\[ O_{\text{Add}} = - \sum \| X - W \|_1 \]  

Based on the above introduction, the search space in ShiftAddNAS incorporates all the four different types of blocks (i.e., Attn, Conv, Shift, and Add), aiming to push forward both NNs’ accuracy and efficiency. Note that we refer to all operators as blocks, and adopt block based search space because it has been evidenced and proven that block based ones can reduce the search space size and lead to more accurate architecture ranking/rating (Li et al., 2020b;a).

**Hardware cost.** As mentioned, multiplication-based operators (e.g., Attn and Conv) favor a superior accuracy yet is not hardware efficient, while multiplication-free operators (e.g., Shift and Add) favor a better hardware efficiency yet can hurt the achievable accuracy. Specifically, as shown in Fig. 1, bitwise shifts can save as high as $196 \times$ and $24 \times$ energy costs over multiplications, when implemented in a 45nm CMOS technology and SOTA FPGA (Xilinx Inc.), respectively; with a 16-bit precision, bitwise shifts may achieve at least $9.7 \times$ and $1.45 \times$ average power and area savings than multipliers (Elhoushi et al., 2021); and similarly, additions can save up to $196 \times$ and $31 \times$ energy costs over multiplications in 32-bit fixed-point (FIX32) formats, and $47 \times$ and $4.1 \times$ energy costs in 32-bit floating-point (FP32) formats, when implemented in a 45nm CMOS technology and SOTA FPGA (Xilinx Inc.), respectively, while leading to $1.84 \times$, $25.5 \times$, and $7.83 \times$ area savings than multiplications in a 45nm CMOS technology with FP32, FIX32, and FIX8 formats, respectively (Chen et al., 2021c).

**Supernet for NLP tasks.** Based on the above search space, we construct a supernet for the convenience of search following SOTA one-shot NAS methods (Cai et al., 2018; Guo et al., 2020) by estimating the performance of each candidate hybrid model (i.e., subnet) without fully training it. As shown in Fig. 2 (a), each macro-block in the supernet includes all the aforementioned four candidate blocks and three multi-branch combinations (e.g., Attn+Conv) along the channel dimension for capturing both global and local context information following (Wu et al., 2020), where the candidate blocks in the same layer are isolated with each followed by two-layer MLPs and enable elastic embedding dimension, head numbers, and MLP hidden dimension for fine-grained search for efficient NNs as (Wang et al., 2020a). Overall, our supernet for NLP tasks contains about $10^{14}$ subnet candidates, and the searchable choices are listed in Tab. 1. During training, all possible subnets are uniformly sampled and only one path is activated for each layer at run-time considering the practical concern on memory consumption for supernet training. For ease of evaluation, we incorporate common treatments of NAS in our supernet design. First, for the elastic dimensions mentioned above, all subnets share the front portion of weight channels or attention heads of the largest dimension. Second, all decoder blocks can take the last one, two, or three encoder blocks as inputs for abstracting both high-level and low-level information (Wang et al., 2020a). Note that the number of decoder blocks are also searchable and the conv, shift and add operators are disabled for decoder blocks, as they are observed to be sensitive and activating those paths might hurt the accuracy (You et al., 2020a; Wu et al., 2019b).

**Supernet for CV tasks.** Different from the commonly used elastic hidden dimension design for NLP tasks, various spatial resolutions or scales are essential for CV tasks. As such, to ensure more capable feature description of the searched NNs, we adopt a multi-resolution supernet design. As shown in Fig. 2 (b), the supernet incorporates flexible downsampling options, where the spatial resolution for each layer can either stay unchanged or be reduced to half of its previous layer’s scale until reaching the smallest resolution. In this way, the four candidate blocks can work collaboratively to deliver the multiscale features required by most CV tasks. Overall, our supernet contains about $10^{9}$ subnets,
for which the detailed searchable choices are summarized in Tab. 2. Note that the Attn block is followed by two-layer MLPs and we also include a residual connection for each block as inspired by (Srinivas et al., 2021). During training, the supernet performs uniform sampling and only activates one path of the chosen resolution and block type for each layer as for the NLP tasks.

### 3.2. ShiftAddNAS: Search Method

#### 3.2.1. Background and Formulation of One-Shot NAS

We adopt one-shot NAS for improved search efficiency, i.e., assuming that the subnet candidates can directly inherit their weights from the supernet, following SOTA NAS works. Such a strategy is commonly referred as weight sharing. Specifically, the supernet $\mathcal{N}$ with parameters $W$ is trained to obtain the weights for all subnets within the search space $\mathcal{S}$. Since the supernet training and architecture search are decoupled in one-shot NAS, it usually requires two-level optimization: supernet training and architecture evaluation as defined below:

$$W_\mathcal{S} = \arg \min_W L_{\text{train}}(\mathcal{N}(\mathcal{S}, W)),$$

$$a^* = \arg \max_{a \in \mathcal{S}} ACC_{\text{val}}(\mathcal{N}(a, W_\mathcal{S}(a))).$$

where $\mathcal{N}(\mathcal{S}, W)$ represents all possible candidate subnets within the search space. We first train the supernet by uniformly sampling different subnets $a$ from $\mathcal{S}$ as formulated in Eq. (5), after which all subnet candidates $a$ directly inherit their corresponding weights $W_\mathcal{S}(a)$ from the supernet $W_\mathcal{S}$. Finally, we evaluate the accuracy $ACC_{\text{val}}(\cdot)$ of each path on the validation set and search for the best subnet with the highest accuracy as formulated in Eq. (6).

#### 3.2.2. Proposed Heterogeneous Weight Sharing Strategy

**Dilemma of vanilla ShiftAddNAS.** The target hybrid search space of ShiftAddNAS inevitably enlarges the supernet due to the newly considered operators. As such, activating all block choices without weight sharing as (Gong et al., 2019; Cai et al., 2018) can easily explode the memory consumption of NAS. On the other hand, directly sharing weights among different operators as (Chen et al., 2021b) will lead to biased search, especially for our hardware-inspired hybrid search space where weights and activations of different operators follow heterogeneous distributions, e.g., weights of the Conv and Add blocks follow a Gaussian and Laplacian distribution, respectively, as shown in Fig. 7 and also highlighted in (Chen et al., 2020) (more visualization can be found at Appendix B). Specifically, if we follow the existing weight sharing strategy to enforce a homogeneous weight distribution among different operators during training the supernet, the resulting weights will not match the heterogeneous weight distributions of independently trained optimal hybrid subnets. That is to say, for NAS with the target hybrid search space, there exists an optimization gap between the goals of weight sharing optimization and individual subnet optimization, where the former is approximated while the latter is accurate (Xie et al., 2020). Hence, naively adopting the homogeneous weight sharing strategy can lead to inconsistent architecture ranking, which is a major issue associated with one-shot NAS as pointed out by (Chu et al., 2019; You et al., 2020b).

**Proposed solution: heterogeneous weight sharing.** To tackle the aforementioned dilemma, we propose a heterogeneous weight sharing strategy that can simultaneously reduce the supernet size corresponding to the target hybrid search space and allow weights of different blocks to fol-
we consider two machine translation

\[ \mathcal{L}_S = \mathcal{L}_{CE} + \mathcal{L}_{KL} = - \frac{1}{N} \sum_{i=1}^{N} P(y_i|x_i) \log(P(\hat{y}_i|x_i)) + D(P_{\text{conv}}(W_S)||N(0, I)) + D(P_{\text{add}}(T(W_S)))||L_p(0, \lambda), \]

where \(\{x_i, y_i\}_{i=1}^{N}\) are training data, \(\hat{y}\) denotes the output prediction, and \(D_{KL}(p||q) = - \int p(z) \log\left(\frac{p(z)}{q(z)}\right) dz\) measures the KL-divergence between two distributions. During training, we maintain a shared weight pool for each layer to share weights across all the Conv, Add, and Shift blocks, as illustrated in Fig. 4 (a). Meanwhile, weights of the Conv blocks directly leverage the corresponding ones in the shared weight pool for both forward and backpropagation, while being encouraged to follow a Gaussian distribution by the objective function; weights of the Shift blocks quantize the shared weights of Gaussian distribution to powers of two before multiplying with the input features, we follow (Elhoushi et al., 2021) to backpropagate the gradients; and for the Add blocks, we make use of a learnable transformation kernel \(T(\cdot)\) to map the shared weights of Gaussian distribution to a Laplacian distribution. For the learnable transformation kernel as captured by Eq. (8), the core idea is to apply a piece-wise linear transformation after flattening and sorting the weights in a descending order, and then to reshape and rearrange the transformed weights back to their positions before sorting.

\[ T(W) = \sum_{i=0}^{d-1} \alpha_i \times W_{s \times s \times (i+1)}, \]

where \(\{\alpha_i\}_{i=1}^{d}\) denote the learnable parameters in \(T(\cdot)\), \(\{W_i\}_{i=1}^{n}\) represent the sorted weights (a total of \(n\) in the pool, \(s = n/d\) denotes an interval within which the transformation is linear, as illustrated in Fig. 4 (b). As validated in our visualization of supernet weights (e.g., Fig. 7), such a transformation kernel can successfully transform the shared weights of Gaussian to the desired Laplacian distribution, which is consistent with previous observations about kernel learning via linear transformation (Jain et al., 2012). In our design, each layer has its own learnable kernel \(T(\cdot)\) with a dimension \(d\) of 200 throughout all the experiments as we observed that such a dimension is adequate to learn the transformation across all the models and datasets, leading to over 40\% supernet size reduction while only incurring a negligible (< 0.01\% of the supernet size and computational costs) search overhead. After the supernet is well trained, evolution search is applied to find the optimal subnets.

4. Experiment Results

In this section, we first describe our experiment setups, and then benchmark ShiftAddNAS over SOTA CNNs, Transformers, and previous NAS frameworks on both NLP and CV tasks. After that, we conduct ablation studies regarding ShiftAddNAS’s heterogeneous weight sharing strategy.

4.1. Experiment Setups

Datasets, baselines, and evaluation metrics. For NLP tasks, we consider two machine translation datasets, WMT’14 English to French (En-Fr) and English to German (En-De), which consist of 36.3M and 4.5M pairs of training sentences, respectively. The train/val/test splits follow the tradition as in (Wang et al., 2020a; Gehring et al., 2017). We consider five baselines: Transformer (Vaswani et al., 2017), Lightweight Conv (Wu et al., 2019b), Lite Transformer (Wu et al., 2020), and two previous NAS works including Evolved Transformer (So et al., 2019) and HAT (Wang et al., 2020a). We evaluate in terms of five evaluation metrics: the number of parameters/FLOPs, achieved BLEU, and hardware energy and latency measured on a SOTA accelerator Eyeriss (Chen et al., 2016) clocked at 250MHz, where the BLEU is calculated with case-sensitive tokenization following (Wang et al., 2020a). For CV tasks, we consider the ImageNet dataset and four kinds of SOTA baselines: four multiplication-free CNNs (Chen et al., 2020; Xu et al., 2020; Courbariaux et al., 2016; Elhoushi et al., 2021), two CNNs (He et al., 2016; Hu et al., 2018), five Transformers (Dosovitskiy et al., 2021; Touvron et al., 2021; Yuan et al., 2021; Han et al., 2021; Srinivas et al., 2021), and four NAS works (i.e., HR-NAS (Ding et al., 2021), BossNAS (Li et al., 2021), AutoFormer (Chen et al., 2021b), and VITAS (Su et al., 2021)). Similar to those for the NLP tasks, we adopt five evaluation metrics: the number of parameters/MACs, achieved accuracy, and hardware energy and latency.

Search and training settings. For NLP tasks, after training
the supernet for 40K steps, we adopt an evolutionary algo-
rithm (Wang et al., 2020a) to search for subnets with
various latency and FLOPs constraints. During search, we follow
(Wang et al., 2020a) to adopt a three-layer NN to measure
the latency, which is accurate with an average prediction
error of < 5%. The searched subnets are then retrained
from scratch for another 40K steps. For CV tasks, we follow
(Chen et al., 2021b) to conduct an evolutionary search
with FLOPs constraints for 20 steps. We train both the
supernet and searched subnets using the same recipe and
hyperparameters as DeiT (Touvron et al., 2021). More de-
tails regarding search and training settings can be found in
Appendix E.

4.2. ShiftAddNAS vs. SOTA Methods on NLP Tasks
We compare ShiftAddNAS with SOTA language models on
two NLP tasks to evaluate its efficacy. Fig. 5 shows that Shif-
tAddNAS consistently outperforms all the baselines in terms
of BLEU scores and FLOPs. Specifically, ShiftAddNAS
with full precision achieves 11.8% ∼ 73.6% FLOPs reduc-
tions while offering a comparable or better BLEU score
(-0.3 ∼ +1.1), over all the full precision baselines. To bench-
mark with Lite Transformer (8-bit) which is dedicated for
mobile devices, we refer to a SOTA quantization technique
(Banner et al., 2018) for quantizing ShiftAddNAS to 8-bit
fixed point: ShiftAddNAS (8-bit) achieves +1.8 ∼ +4.9
BLEU scores improvements over Lite Transformer (8-bit),
while offering 5.0% ∼ 82.7% FLOPs reductions, and ag-
gressively reduces 91.6% ∼ 98.4% FLOPs as compared to
all the full-precision baselines with comparable BLEU
scores (-0.1 ∼ +0.3). Note that for quantized models, we
follow (Zhou et al., 2016) to use FLOPs × (Bit/32)² for
calculating the effective FLOPs which is proportional to
the number of bit-operations. We further compare various
aspects of ShiftAddNAS with all baselines in Tab. 3. As
illustrated in this Table, ShiftAddNAS consistently outper-
forms the baselines, e.g., achieves up to +2 BLEU scores
improvement when comparing ShiftAddNAS (8-bit) with
Lite Transformer on WMT'14 En-Fr and 69.1% and 69.2%
energy and latency savings when comparing ShiftAddNAS
with Transformer on WMT'14 En-De, with a comparable
or even fewer model parameters and FLOPs.

4.3. ShiftAddNAS vs. SOTA Methods on CV Tasks
We further compare ShiftAddNAS over SOTA baselines on
ImageNet to evaluate its effectiveness on the image classifi-
cation task. As shown in Tab. 4, 11, ShiftAddNAS outper-
forms a wide range of baselines. Here we refer MACs as
Multiply–accumulate or Shift-accumulate operations. For
example, ShiftAddNet-T0 (searched with a 4.5G MACs con-
straint) with 3.7G MACs achieves an improved top-1 accu-

cacy of (1) +5.3% ∼ +26.3% over SOTA multiplication-free
CNNs, (2) +0.7% ∼ +6.0% over SOTA CNNs, (3) +0.4% ∼
+7.6% over SOTA Transformers, (4) +1.3% ∼ +4.8%
| Model              | Top-1 Acc. | Top-5 Acc. | Params | Res. | MACs  | #Mult. | #Add  | #Shift | Model Type |
|--------------------|------------|------------|--------|------|-------|--------|-------|--------|------------|
| AdderNet           | 74.9%      | 91.7%      | 26M    | 224  | 3.9G  | 0.1G   | 7.6G  | 0      | Multi-free |
| DeepShift-PS       | 71.9%      | 90.2%      | 52M    | 224  | 3.9G  | 0.1G   | 3.9G  | 3.8G   | Multi-free |
| ShiftAddNet        | 72.3%      |            | 64M    | 224  | 10G   | 0.1G   | 16G   | 3.9G   | Multi-free |
| ResNet-50          | 76.1%      | 92.9%      | 26M    | 224  | 3.9G  | 3.9G   | 3.9G  | 0      | CNN        |
| ResNet-101         | 77.4%      | 94.2%      | 45M    | 224  | 7.6G  | 7.6G   | 7.6G  | 0      | CNN        |
| ViT-B/16           | 77.9%      |            |        |      |       |        |       |        | Transformer |
| DeiT-S             | 81.2%      |            |        |      |       |        |       |        | Transformer |
| VITAS              | 77.4%      | 93.8%      |        |      |       |        |       |        | Transformer |
| Autoformer-S       | 81.7%      | 95.7%      |        |      |       |        |       |        | Transformer |
| BoT-50             | 78.3%      | 94.2%      |        |      |       |        |       |        | CNN + Trans. |
| BossNAS-T0         | 80.5%      | 95.0%      |        |      |       |        |       |        | CNN + Trans. |
| ShiftAddNAS-T0     | 82.1%      | 95.8%      |        |      |       |        |       |        | Hybrid     |
| ShiftAddNAS-T0↑    | 82.6%      | 96.2%      |        |      |       |        |       |        | Hybrid     |
| T2T-ViT-19         | 81.9%      |            |        |      |       |        |       |        | Transformer |
| Autoformer-B       | 82.4%      | 95.7%      |        |      |       |        |       |        | Transformer |
| BoTNet-S1-59       | 81.7%      | 95.8%      |        |      |       |        |       |        | CNN + Trans. |
| BossNAS-T1         | 82.2%      | 95.8%      |        |      |       |        |       |        | CNN + Trans. |
| ShiftAddNAS-T1     | 82.7%      | 96.1%      |        |      |       |        |       |        | Hybrid     |
| ShiftAddNAS-T1↑    | 83.0%      | 96.4%      |        |      |       |        |       |        | Hybrid     |
| ViT-B/16           | 77.9%      |            |        |      |       |        |       |        | Transformer |
| DeiT-S             | 81.2%      |            |        |      |       |        |       |        | Transformer |
| VITAS              | 77.4%      | 93.8%      |        |      |       |        |       |        | Transformer |
| Autoformer-S       | 81.7%      | 95.7%      |        |      |       |        |       |        | Transformer |
| BoT-50             | 78.3%      | 94.2%      |        |      |       |        |       |        | CNN + Trans. |
| BossNAS-T0         | 80.5%      | 95.0%      |        |      |       |        |       |        | CNN + Trans. |
| ShiftAddNAS-T0     | 82.1%      | 95.8%      |        |      |       |        |       |        | Hybrid     |
| ShiftAddNAS-T0↑    | 82.6%      | 96.2%      |        |      |       |        |       |        | Hybrid     |
| T2T-ViT-19         | 81.9%      |            |        |      |       |        |       |        | Transformer |
| Autoformer-B       | 82.4%      | 95.7%      |        |      |       |        |       |        | Transformer |
| BoTNet-S1-59       | 81.7%      | 95.8%      |        |      |       |        |       |        | CNN + Trans. |
| BossNAS-T1         | 82.2%      | 95.8%      |        |      |       |        |       |        | CNN + Trans. |
| ShiftAddNAS-T1     | 82.7%      | 96.1%      |        |      |       |        |       |        | Hybrid     |
| ShiftAddNAS-T1↑    | 83.0%      | 96.4%      |        |      |       |        |       |        | Hybrid     |

Table 5: Comparison with FBNet on CIFAR-10/100 dataset.

| Dataset  | Methods  | Accuracy | MACs  | #Mult. | #Add  | Shift | Latency Savings |
|----------|----------|----------|-------|--------|-------|-------|-----------------|
| CIFAR-10 | FBNet    | 95.09%   | 47M   | 47M    | 47M   | 0     | -              |
|          | ShiftAddNAS | 95.83% (+0.74%) | 47M | 17M | 38M | 21M | 33.80%          |
| CIFAR100 | FBNet    | 77.86%   | 55M   | 55M    | 55M   | 0     | -              |
|          | ShiftAddNAS | 78.64% (+0.58%) | 52M | 22M | 62M | 21M | 38.60%          |

Table 6: Ablation study of ShiftAddNAS w/ (1) naive and (2) heterogeneous weight sharing.

| ShiftAddNAS | Kendall τ | Pearson R | Spearman ρ |
|-------------|-----------|-----------|------------|
| w/ Naive WS | 0.49      | 0.67      | 0.69       |
| w/ HWS      | 0.54      | 0.75      | 0.74       |

4.4. ShiftAddNAS vs. SOTA under Small MACs

To fairly compare with baselines with smaller MACs, we implemented our proposed hybrid search space and heterogeneous weight sharing (HWS) techniques on top of the FBNet search space, and evaluated the performance on CIFAR-10/100. As shown in the Tab. 5, our ShiftAddNAS consistently boosts a +0.74% and +0.58% accuracy over FBNet and leads to 33.8% and 38.6% latency savings on CIFAR-10 and CIFAR-100, respectively.

4.5. Ablation Studies of Heterogeneous Weight Sharing

We conduct ablation studies on ShiftAddNAS’s heterogeneous weight sharing (HWS) strategy, as shown in Tab. 6.
Table 7: Comparisons of different search space variants.

| Operators       | Our Space on ImageNet | FBNet Space on CIFAR100 |
|-----------------|-----------------------|-------------------------|
|                 | Acc. | Mult. | Add | Shift | Acc. | Mult. | Add | Shift |
| Attn&Conv       | 81.6% | 5.8G | 5.8G | 0     | 77.9% | 55M | 55M | 0     |
| Shift&Add       | 76.8% | 0.1G | 5.3G | 3.2G | 71.0% | 3M | 48M | 35M |
| Attn&Conv&Add   | 82.4% | 5.6G | 7.2G | 0     | 78.3% | 30M | 60M | 0     |
| All             | 82.6% | 3.6G | 4.9G | 1.4G | 78.6% | 22M | 62M | 21M |

Figure 7: The weight distribution of Conv and Add layers.

First, for searching on ImageNet, we use three ranking correlation metrics: Kendall τ, Pearson R, and Spearman ρ, to measure the ranking correlation between ShiftAddNAS w/ and w/o HWS and find that the former leads to a higher ranking correlation than the naive WS. Second, the proposed HWS leads to more accurate searched subnets. Specifically, the searched subnet achieves a +1.4% higher accuracy than that of naive WS, at comparable or even smaller energy and latency costs. Also, HWS effectively reduces the supernet size from 615M (w/o WS) to 364M (41% savings). This set of ablation studies validate the effectiveness of our proposed HWS strategy. In addition, the search cost analysis of ShiftAddNAS is placed in Appendix A.

4.6. Ablation Studies of Conv/Add Distribution

We visualize the weight distributions of Conv/Add layers in Supernets under three scenarios, (1) w/o WS; (2) HWS w/o KL loss; (3) HWS, as shown in Fig. 7. We consistently observe that weights of Conv/Add layers follow Gaussian and Laplacian distribution, especially when applying the introduced KL loss.

4.7. Ablation Studies of Search Space

To validate the necessity of considered searchable blocks, we consider three scenarios to breakdown the search space benefits, i.e., only using: (1) Attn & Conv (i.e., BossNAS); (2) Shift & Add; and (3) Attn & Conv & Add, respectively. Additionally, we also conduct such controlled experiments on top of FBNet search space (ignore Attn). In Tab. 7, we consistently see that our search space consisting of all operators outperforms (1) in terms of both accuracy and efficiency; achieves much higher accuracy than (2); and gains slightly better accuracy-efficiency trade-offs than (3).

5. Conclusion

We propose ShiftAddNAS for searching for multiplication-reduced NNs incorporating both powerful yet costly multiplications and efficient yet less powerful shift and add operators for marrying the best of both worlds. ShiftAddNAS is made possible by integrating: (1) the first hybrid search space that incorporates both multiplication-based and multiplication-free operators; and (2) a novel heterogeneous weight sharing strategy that allows different operators to follow heterogeneous distributions for alleviating the dilemma of either inefficient search or inconsistent architecture ranking when searching hybrid NNs. Extensive experiments on both NLP and CV tasks demonstrate the superior accuracy and efficiency of ShiftAddNAS’s searched NNs over various SOTA baselines, opening up a new perspective in searching for more accurate and efficient NNs.

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A. Evaluate the Search Cost

We further supply the total search cost of ShiftAddNAS on both NLP tasks and CV tasks in Table 8 and 9, respectively. For NLP tasks, with one Nvidia V100 GPU, ShiftAddNAS uses on average 9.3 GPU days (Gds) for searching which is comparable to HAT (Wang et al., 2020a) and 9,821× less than the Evolved Transformer (So et al., 2019). For CV tasks, ShiftAddNAS uses on average 8.9 Gds for searching which is 11% and 82% less than DARTS (Liu et al., 2018) and BossNAS (Li et al., 2021), respectively. In addition, we provide a concrete breakdown analysis of ShiftAddNAS search cost in Table 10. For NLP tasks, ShiftAddNAS needs on average 8.5 Gds for supernet training and 0.8 Gds for architecture searching; For CV tasks, ShiftAddNAS takes on average 7.7 Gds for supernet training and 1.2 Gds for architecture searching.

| Methods      | Search Cost |
|--------------|-------------|
| Evolved Trans.| 91,334 Gds  |
| HAT          | 9.3 Gds     |
| ShiftAddNAS  | 9.3 Gds     |

| Methods | Search Cost |
|---------|-------------|
| DARTS   | 50 Gds      |
| BossNAS | 10 Gds      |
| ShiftAddNAS | 8.9 Gds   |

Table 8: Search cost on NLP tasks.

Table 9: Search cost on CV tasks.

Table 10: Breakdown analysis of the search cost of ShiftAddNAS.

|                     | NLP   | CV    |
|---------------------|-------|-------|
| Supernet Train      | 8.5 Gds | 7.7 Gds |
| Arch. Search        | 0.8 Gds | 1.2 Gds |

B. Visualization of the Heterogeneous Weight Distributions

For better understanding of the proposed heterogeneous weight sharing strategy, we further supply the visualization of the heterogeneous weight distributions in Conv/Add/Shift layers, respectively, as shown in the Fig. 8.

![Weights in Conv](Gaussian)

![Weights in Add](Laplacian)

![Weights in Shift](Discrete)

(a) Weights in Conv  (b) Weights in Add  (c) Weights in Shift

Figure 8: Visualization of the heterogeneous weight distributions in Conv/Add/Shift layers.

C. Complete Comparison between ShiftAddNAS and SOTA on CV Tasks

We further compare ShiftAddNAS over SOTA baselines on ImageNet to evaluate its effectiveness on the image classification task, and supply the complete comparing results to Tab. 11 below. Note that we report both the rank #1 searched architecture with the highest accuracy that contains Shift and Conv blocks, and rank #2 searched architecture contains additional two Add blocks and achieves a 82.8% top-1 accuracy on ImageNet with 8.4G MACs (#Mult: 7.4G; #Add: 9.1G; #Shift: 0.5G).

D. Visualization of the Searched Architecture

For better understanding of the searched architecture, we provide the visualization of the searched architecture ShiftAddNAS-T1↑1 and ShiftAddNAS-T1↑2 in Fig. 9 and Fig. 10, respectively. The searched architecture ShiftAddNAS-T1↑1 contains four Shift blocks, and achieves 83% top-1 test accuracy on ImageNet with 8.5G MACs (#Mult: 7.1G; #Add: 8.5G; #Shift: 1.4G). The searched architecture ShiftAddNAS-T1↑2 contains two Add blocks and one Shift block, and achieves 82.8% top-1 test accuracy on ImageNet with 8.4G MACs (#Mult: 7.4G; #Add: 9.1G; #Shift: 0.5G). Moreover, the searched architecture prefers Conv as early blocks while consider Attn as later blocks, which is also consistent with the previous empirical observation that early convolutions help the overall performance (Xiao et al., 2021).

More discussion for the searched architectures. The performance of the searched top architectures are quite close (e.g., the accuracy difference between rank #1 and rank #2 is smaller than 0.2%), and we also quantitatively measure the ratio breakdown of different operators in our searched top-10 architectures (Attn: 30%; Conv: 43%; Shift: 15%; Add: 12%). We see that the overall ratio of Add operators is quite comparable with that of Shift operators, thus our understanding is that the searched top architectures benefit from a relatively more balanced combination/contribution of all operators to
after training the supernet for 40K steps, we adopt an evolutionary algorithm (Wang et al., 2020a) to search for subnets with various latency and FLOPs constraints ranging from 1.5G to 4.5G for 30 steps with a population of 125, a crossover population of 50, and a mutation population of 50 with a probability of 0.3. During search, measuring latency for each chosen subnet can be time-consuming. Instead, we estimate the latency using a three-layer NN trained with encoding architecture parameters as features and measured latency as labels following (Wang et al., 2020a). The latency predictor is accurate with an average prediction error of $<5\%$. The searched subnets are then retrained from scratch for another 40K steps with an Adam optimizer and a cosine learning rate (LR) scheduler, where the LR is linearly warmed up from $10^{-7}$ to $10^{-3}$ and then annealed (same for training supernets). For CV tasks, we conduct an evolutionary search with FLOPs constraints for 20 steps with a population of 50, a crossover population of 25, and a mutation population of 25 with a probability of 0.2 following (Chen et al., 2021b). We train both the supernet and searched subnets using the same recipe and hyperparameters as DeiT (Touvron et al., 2021). Note that the position encoding in the attention blocks is replaced with a 2D sinusoidal encoding for more accurate and efficient neural networks.

### E. Detailed Search and Training Settings

**For NLP tasks**, after training the supernet for 40K steps, we adopt an evolutionary algorithm (Wang et al., 2020a) to search for subnets with various latency and FLOPs constraints ranging from 1.5G to 4.5G for 30 steps with a population of 125, a crossover population of 50, and a mutation population of 50 with a probability of 0.3. During search, measuring latency for each chosen subnet can be time-consuming. Instead, we estimate the latency using a three-layer NN trained with encoding architecture parameters as features and measured latency as labels following (Wang et al., 2020a). The latency predictor is accurate with an average prediction error of $<5\%$. The searched subnets are then retrained from scratch for another 40K steps with an Adam optimizer and a cosine learning rate (LR) scheduler, where the LR is linearly warmed up from $10^{-7}$ to $10^{-3}$ and then annealed (same for training supernets). For CV tasks, we conduct an evolutionary search with FLOPs constraints for 20 steps with a population of 50, a crossover population of 25, and a mutation population of 25 with a probability of 0.2 following (Chen et al., 2021b). We train both the supernet and searched subnets using the same recipe and hyperparameters as DeiT (Touvron et al., 2021). Note that the position encoding in the attention blocks is replaced with a 2D sinusoidal encoding for more accurate and efficient neural networks.
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Figure 9: Visualization of the searched architecture ShiftAddNAS-T1$^1$ with 83% top-1 test accuracy on ImageNet.

Figure 10: Visualization of the searched architecture ShiftAddNAS-T1$^2$ with 82.8% top-1 test accuracy on ImageNet.

depthwise convolution following (Li et al., 2021) for reducing the computational complexity.