**Abstract**

If NAS methods are solutions, what is the problem? Most existing NAS methods require two-stage parameter optimization. However, performance of the same architecture in the two stages correlates poorly. In this work, we propose a new problem definition for NAS, task-specific end-to-end, based on this observation. We argue that given a computer vision task for which a NAS method is expected, this definition can reduce the vaguely-defined NAS evaluation to i) accuracy of this task and ii) the total computation consumed to finally obtain a model with satisfying accuracy. Seeing that most existing methods do not solve this problem directly, we propose DSNAS, an efficient differentiable NAS framework that simultaneously optimizes architecture and parameters with a low-biased Monte Carlo estimate. Child networks derived from DSNAS can be deployed directly without parameter retraining. Comparing with two-stage methods, DSNAS successfully discovers networks with comparable accuracy (74.4%) on ImageNet in 420 GPU hours, reducing the total time by more than 34%.

1. Introduction

The success of deep learning is partially built upon the architecture of neural networks. However, the variation of network architectures always incurs unpredictable changes in performance, causing tremendous efforts in ad hoc architecture design. Neural Architecture Search (NAS) is believed to be promising in alleviating this pain. Practitioners from the industry would like to see NAS techniques that automatically discover task-specific networks with reasonable performance, regardless of their generalization capability. Therefore, NAS is always formulated as a hyper-parameter optimization problem, whose algorithmic realization spans evolution algorithm [21, 7], reinforcement learning [28], Bayesian optimization [9], Monte Carlo Tree Search [25], and differentiable architecture search [14, 27, 3]. Recently, these algorithmic frameworks have exhibited pragmatic success in various challenging tasks, e.g. semantic segmentation [12] and object detection [4] etc.

However, even as an optimization problem, NAS is almost vaguely defined. Most of the NAS methods proposed recently are implicitly two-stage methods. These two stages are searching and evaluation (or retraining). While the architecture optimization process is referring to the searching stage, in which a co-optimization scheme is designed for parameters and architectures, there runs another round of parameter optimization in the evaluation stage, on the same set of training data for the same task. This is to some extent contradicting the norm in a machine learning task that no optimization is allowed in evaluation. A seemingly sensible argument could be that the optimization result of NAS is only the architecture, and the evaluation of an architecture is to check its performance after retraining. There is certainly no doubt that architectures that achieve high performance when retrained from scratch are reasonable choices.
for deployment. But is this search method still valid if the searched architecture does not perform well after retraining, due to the inevitable difference of training setup in searching and evaluation?

These questions can only be answered with an assumption that the final searching performance can be generalized to evaluation stage even though the training schemes in two stages are different. Specifically, differences in training schemes may include different number of cells, different batch sizes, and different epoch numbers, etc. Using parameter sharing with efficiency concerns during search is also a usual cause. Unfortunately, this assumption is not a valid one. The correlation between the performance at the end of searching and after the retraining in evaluation is fairly low, as long as the parameter-sharing technique is used [20, 5].

We are thus motivated to rethink the problem definition of neural architecture search. We want to argue that as an application-driven field, there can be a diverse set of problem definitions, but every one of them should not be vague. And in this work, we put our cards on the table: we aim to tackle the task-specific end-to-end NAS problem. Given a task, defined by a data set and an objective (e.g. training loss), the expected NAS solution optimizes architecture and parameters to automatically discover a neural network with reasonable (if not optimal by principle) performance. By the term end-to-end, we highlight the solution only need a single-stage training to obtain a ready-to-deploy neural network of the given task. And the term task-specific highlights the boundary of this solution. The searched neural network can only handle this specific task. We are not confident whether this neural network generalizes well in other tasks. Rather, what can be expected to generalize is this NAS framework.

Under this definition, the evaluation metrics of a proposed framework become clear, namely searching efficiency and final performance. Scrutinizing most existing methods in these two metrics, we find a big niche for a brand new framework. On one side of the spectrum, gradient-based methods such as ENAS [17], DARTS [14], ProxylessNAS [3] require two-stage parameter optimization. This is because in the approximation to make them differentiable, unbounded bias or variance are introduced to their gradients. Two-stage methods always consume more computation than single-stage ones, not only because of another round of training but also the reproducibility issue [11]. On the other side of the spectrum, one-shot methods such as random search [11] and SPOS [7] can be extended to single-stage training. But since they do not optimize the architecture distribution in parameter training, the choice of prior distribution becomes crucial. A uniform sampling strategy may potentially subsume too many resources for satisfying accuracy. Lying in the middle, SNAS [27] shows a proof of concept, where the derived network maintains the performance in the searching stage. However, the gumbel-softmax relaxation makes it necessary to store the whole parent network in memory in both forward and backward, inducing tremendous memory and computation waste.

In this work, we confront the challenge of single-stage simultaneous optimization on architecture and parameters. Our proposal is an efficient differentiable NAS framework, Discrete Stochastic Neural Architecture Search (DSNAS). Once the search process finishes, the best-performing sub-network is derived with optimized parameters, and no further retraining is needed. DSNAS is built upon a novel search gradient, combining the stability and robustness of differentiable NAS and the memory efficiency of discrete-sampling NAS. This search gradient is shown to be equivalent to SNAS’s gradient at the discrete limit, optimizing the task-specific end-to-end objective with little bias. And it can be calculated in the same round of back-propagation as gradients to neural parameters. Its forward pass and back-propagation only involve the compact subnetwork, whose computational complexity can be shown to be much more friendly than DARTS, SNAS and even ProxylessNAS, enabling large-scale direct search. We instantiate this framework in a single-path setting. The experimental results show that DSNAS discovers networks with comparable performance (74.4%) in ImageNet classification task in only 420 GPU hours, reducing the total time of obtaining a ready-to-deploy solution by 34% from two-stage NAS.

To summarize, our main contributions are as follows:

- We propose a well-defined neural architecture search problem, task-specific end-to-end NAS, under the evaluation metrics of which most existing NAS methods still have room for improvement.

- We propose a plug-and-play NAS framework, DSNAS, as an efficient solution to this problem in large scale. DSNAS updates architecture parameters with a novel search gradient, combining the advantages of policy gradient and SNAS gradient. A simple but smart implementation is also introduced.

- We instantiate it in a single-path parent network. The empirical study shows DSNAS robustly discovers neural networks with state-of-the-art performance in ImageNet, reducing the computational resources by a big margin over two-stage NAS methods. We have made our implementation public.

2. Problem definition of NAS

2.1. Two-Stage NAS

Most existing NAS methods involve optimization in both searching stage and evaluation stage. In the searching
stage, there must be parameter training and architecture optimization, even though they may not run simultaneously. The ideal way is to train all possible architectures from scratch and then select the optimal one. However, it is infeasible with the combinatorial complexity of architecture. Therefore, designing the co-occurrence of parameter and architecture optimization to improve efficiency is the main challenge of any general NAS problems. This challenge has not been overcome elegantly yet. The accuracy at the end of the searching stage has barely been reported to be satisfying. And an ad hoc solution is to perform another round of parameter optimization in the evaluation stage.

Optimizing parameters in evaluation stage is not normal in traditional machine learning. Normally, the data set provided is divided into training set and validation set. Ones do learning in the training stage, with data from the training set. Then the learned model is tested on the withheld validation set, where no further training is conducted. With the assumption that training data and validation data are from the same distribution, the learning problem is reduced to an optimization problem. Ones can hence be confident to expect models with high training accuracy, if the assumption is correct, have high evaluation accuracy.

Allowing parameter retraining in the evaluation stage makes NAS a vaguely defined machine learning problem. Terming problems as Neural Architecture Search give people an inclined interpretation that only the architecture is the learning result, instead of parameters. But if the searched architecture is the answer, what is the problem? Most NAS methods claim they are discovering best-performing architecture in the designated space efficiently [3, 7, 9], but what specifically does best-performing mean? Given that retraining is conducted in evaluation stage, ones may naturally presume it is a meta-learning-like hyperparameter problem. Then the optimization result should exhibit some meta-level advantages, such as faster convergence, better optimum or higher transferability, etc. These are objectives that ones are supposed to state clearly in a NAS proposal. Nonetheless, objectives are only implicitly conveyed (mostly better optimum) in experiments.

Defining problem precisely is one of the milestones in scientific research, whose direct gift in a machine learning task is a clear objective and evaluation metric. Subsequent efforts can then be devoted into validating if the proposed learning loss is approximating a necessary and sufficient equivalence of this objective. Unfortunately, under this criterion, most existing two-stage NAS methods are reported [20, 11] failing to prove the correlation between the searching accuracy and the retraining accuracy.

2.2. Task-specific end-to-end NAS

Seeing that the aforementioned dilemma lies in the ambiguity in evaluating an architecture alone, we propose a type of problem termed task-specific end-to-end NAS, the solution to which should provide a ready-to-deploy network with optimized architecture and parameters.

Task refers to generally any machine learning tasks (in this work we discuss computer vision tasks specifically). A well-defined task should at least have a set of data representing its functioning domain, a learning objective for the task-specific motives e.g. classification, segmentation, etc. And the task is overwritten if there is a modification in either factor, even a trivial augmentation in the data. In other words, task-specific sets a boundary on what we can expect from the searched result and what cannot. This can bring tremendous operational benefits to industrial applications.

End-to-end highlights that, given a task, the expected solution can provide a ready-to-deploy network with satisfying accuracy, the whole process of which can be regarded as a black-box module. Theoretically, it requires a direct confrontation of the main challenge of any general NAS problem, i.e. co-optimizing parameter and architecture efficiently. Empirically, task-specific end-to-end is the best description of NAS’s industrial application scenarios: i) the NAS method itself should be generalizable for any off-the-shelf tasks; and ii) when applied to a specific task, practitioners can at least have some conventional guarantees on the results. Basically, it is to reduce vaguely defined NAS problems to established tasks.

The evaluation metrics become clear under this problem definition. The performance of the final result is, by principle, the accuracy in this task. And the efficiency should be calculated based on the time from this NAS solver starts taking data to it outputs the neural network whose architecture and parameters are optimized. This efficiency metric is different from all existing works. For two-stage methods, the time for both searching and evaluation should be taken into account in this metric. Therefore, their efficiency may not be as what they claim. Moreover, two-stage methods do not optimize the objective higher accuracy of final derived networks in an end-to-end manner.

3. Direct NAS without retraining

3.1. Stochastic Neural Architecture Search (SNAS)

In the literature, SNAS is one of those close to a solution to the task-specific end-to-end NAS problem. Given any task with differentiable loss, the SNAS framework directly optimizes the expected performance over architectures in terms of this task. In this subsection, we provide a brief introduction on SNAS.

Basically, SNAS is a differentiable NAS framework that maintains the generative nature as reinforcement-learning-based methods [28]. Exploiting the deterministic nature of the Markov Decision Process (MDP) of network construction process, SNAS reformulated it as a Markov Chain. This
reformulation leads to a novel representation of the network construction process. As shown in Fig. 2, nodes \( x_i \) (blue lumps) in the DAG represent feature maps. Edges \((i, j)\) (arrow lines) represent information flows between nodes \( x_i \) and \( x_j \), on which \( n \) possible operations \( O_{i,j} \) (orange lumps) are attached. Different from DARTS, which avoids sampling subnetwork with an attention mechanism, SNAS instantiates this Directed Acyclic Graph (DAG) with a stochastic computational graph. Forwarding a SNAS parent network is to first sample random variables \( Z_{i,j} \) and multiplying it to edges \((i, j)\) in the DAG:

\[
O_{i,j} (\cdot) = Z_{i,j}^T O_{i,j} (\cdot).
\]

(1)

O3.2. Discrete SNAS (DSNAS)

In original SNAS [27], to prove its efficiency over ENAS, a policy gradient equivalent of the search gradient is provided

\[
\mathbb{E}_{Z \sim p(Z)} \left[ \frac{\partial L}{\partial \alpha_{i,j}} \right] = \mathbb{E}_{Z \sim p(Z)} \left[ \nabla_{\alpha_{i,j}} \log p(Z) \right] \frac{\partial L}{\partial x_j} O_{i,j}^T (x_j) Z_{i,j} | c,
\]

(4)

where \( Z_{i,j} \) is the gumbel-softmax random variable, \([\cdot]_c \) denotes that \( \cdot \) is a cost independent from \( \alpha \) for gradient calculation. In other words, Eq. 4 and Eq. 3 both optimize the task-specific end-to-end NAS objective i.e. Eq. 2.

In order to get rid of SNAS’s continuous relaxation, we push the \( \lambda \) in the PG equivalent (4) to the limit 0, with the insight that only reparameterization trick needs continuous relaxation but policy gradient doesn’t. The expected search gradient for architecture parameters at each edge becomes:

\[
\lim_{\lambda \to 0} \mathbb{E}_{Z \sim p(Z)} \left[ \frac{\partial L}{\partial \alpha_{i,j}} \right] = \lim_{\lambda \to 0} \mathbb{E}_{Z \sim p(Z)} \left[ \nabla_{\alpha_{i,j}} \log p(Z_{i,j}) \right] \frac{\partial L}{\partial x_j} O_{i,j}^T (x_j) Z_{i,j} | c
\]

\[
= \mathbb{E}_{Z \sim p(Z)} \left[ \nabla_{\alpha_{i,j}} \log p(Z_{i,j}) \right] \frac{\partial L}{\partial x_j} \sum_k O_{i,j}^k (x_j) Z_{i,j}^k | c
\]

(5)

where \( Z_{i,j} \) is a strictly one-hot random variable, \( Z_{i,j}^k \) is the \( k \)th element in it, \([\cdot]_c \) denotes that \( \cdot \) is a cost independent from \( \alpha \) for gradient calculation. Line 3 is derived from line 2 since \( p(Z_{i,j}) = \lim_{\lambda \to 0} p(Z_{i,j}) \) [16]. \( L = \lim_{\lambda \to 0} L. \)

Exploiting the one-hot nature of \( Z_{i,j} \), i.e. only \( Z_{i,j}^i \) on edge \((i, j)\) is 1, others i.e. \( Z_{i,j}^s \) are 0, the cost function can be further reduced to

\[
C(Z_{i,j}) = \sum_k \frac{\partial L}{\partial x_j} O_{i,j}^k (x_j) Z_{i,j}^k
\]

\[
= \frac{\partial L}{\partial x_j} x_j^i Z_{i,j}^i = \frac{\partial L}{\partial x_j} x_j^i
\]

(6)

as long as \( \left| \frac{\partial L}{\partial x_j} O_{i,j}^s (x_j) \right| \neq \infty \). Here \( x_j^i = O_{i,j}^s (x_j) Z_{i,j}^s \) is the output of the operation \( O_{i,j}^s \) chosen at edge \((i, j)\). The equality in line 3 is due to \( Z_{i,j}^i = 1 \).

3.3. Implementation

The algorithmic fruit of the mathematical manipulation in Eq. 6 is a parallel-friendly implementation of Discrete SNAS, as illustrated in Fig. 2. In SNAS, the network construction process is a pass of forward of stochastic computational graph. The whole network has to be instantiated with the batch dimension. In DSNAS we offer an alternative implementation. Note that \( C(Z_{i,j}) = \frac{\partial L}{\partial x_j} \) only needs to be calculated for the sampled subnetworks. And apparently it is also the case for \( \frac{\partial L}{\partial \theta} \). That is to say, the back-propagation of DSNAS only involves the sampled network, instead of the whole parent network. Thus we only instantiate the
subnetwork with the batch dimension for forward and backward. However, the subnetwork derived in this way does not necessarily contain $Z_{i,j}$. If it was not, we would have to calculate $\frac{\partial L}{\partial x_i} \approx z_i \cdot \hat{Z}_{i,j}$. Then the policy gradient loss would explicitly depend on the intermediate result $x^j = O^j(x_i)$, which may need an extra round of forward if it is not stored by the automated differentiation infrastructure. With a smart mathematical manipulation in Eq. 6, ones can simply multiply a dummy 1 to the output of each selected operation, and calculate $C(Z_{i,j})$ with $\frac{\partial L}{\partial x_i \cdot \text{dummy}}$. The whole algorithm is shown in Alg. 1

3.4. Complexity analysis

In this subsection, we provide a complexity analysis of DSNAS, SNAS, and ProxylessNAS. Without loss of generality, we define a parent network with $l$ layers and each layer has $n$ candidate choice blocks. Let the forward time on a sampled subnetwork be $P$, its backward time be $Q$, and the memory requirement for this round be $M$.

As the original SNAS instantiates the whole graph with batch dimension, it needs $n$ times GPU memory and $n$ times calculation comparing to a subnetwork. It is the same case in DARTS.

| Method       | Forward time | Backward time | Memory |
|--------------|--------------|---------------|--------|
| Subnetwork   | $O(P)$       | $O(Q)$        | $O(M)$ |
| SNAS         | $O(nP)$      | $O(nQ)$       | $O(nM)$|
| ProxylessNAS*| $O(nP)$      | $O(nQ)$       | $O(nM)$|
| ProxylessNAS | $O(2P)$      | $O(2Q)$       | $O(2M)$|
| DSNAS        | $O(P)$       | $O(Q)$        | $O(M)$ |

Table 1. Computation complexity comparison between SNAS, ProxylessNAS and DSNAS. ProxylessNAS* indicates its theoretical complexity.

This memory consumption problem of differentiable NAS was first raised by [3]. And they proposed an approximation to DARTS’s optimization objective, with the BinaryConnect [6] technique:

$$\frac{\partial L}{\partial \alpha_{i,j}} = \frac{\partial L}{\partial \hat{Z}_{i,j}} \frac{\partial \hat{Z}_{i,j}}{\partial \alpha_{i,j}} \approx \sum_k \frac{\partial L}{\partial \hat{Z}_{i,j}} \frac{\partial \hat{Z}_{i,j}^k}{\partial \alpha_{i,j}},$$

(7)

where $\hat{Z}_{i,j}$ denotes the attention-based estimator as in DARTS [14], distinct from the discrete random variable $Z_{i,j}$, highlighting how the approximation is being done. But this approximation does not directly save the memory and computation. Different from Eq. 5 and Eq. 6, theoretically, the calculation of Eq. 7 still involves the whole network, as indicated by the summation $\sum$. To reduce memory consumption, they further empirically proposed a path sampling heuristic to decrease the number of paths from $n$ to 2.

Table 1 shows the comparison.
3.5. Progressive early stop

One potential problem in sample-based differentiable NAS is that empirically, the entropy of architecture distribution does not converge to zero, even though comparing to attention-based NAS [14] they are reported [27] to converge with smaller entropy. The non-zero entropy keeps the sampling going on until the end, regardless of the fact that sampling at that uncertainty level does not bring significant gains. To the opposite, it may even hinder the learning on other edges.

To avoid this side-effect of architecture sampling, DSNAS applies a progressive early stop strategy. Sampling and optimization stop at layers/edges in a progressive manner. Specifically, a threshold $h$ is set for the stopping condition:

$$\min\{\alpha_{i,j}^k - \alpha_{i,j}^m, \forall m \neq k\}|\alpha_{i,j}^k = \max\{\alpha_{i,j}\} \geq h.$$  

Once this condition is satisfied on any edge/layer, we directly select the operation choice with the highest probability there, stop its sampling and architecture parameters update in the following training.

3.6. Comparison with one-shot NAS

Different from all differentiable NAS methods, one-shot NAS only do architecture optimization in one-shot, before which they obtain a rough estimation of the graph through either pretraining [1, 7] or an auxiliary hypernetwork [2]. All of them are two-stage methods. The advantage of DSNAS is that it optimizes architecture alongside with parameters, which is expected to save some resources in the pretraining stage. Intuitively, DSNAS rules out non-promising architectures in an adaptive manner by directly optimizing the objective in an end-to-end manner. Although one-shot methods can also have an end-to-end realization, by investing more resources in pretraining, it may take them more epochs to achieve comparable performance as DSNAS. They can also do fine-tuning, but still parameters of the optimal networks are updated less frequently than DSNAS. Ones can expect better performance from DSNAS given equivalent training epochs.

4. Experimental Results

In this section, we first demonstrate why the proposed task-specific end-to-end is an open problem for NAS, by investigating the performance correlation between searching stage and evaluation stage of the two-stage NAS. We then validate the effectiveness and efficiency of DSNAS under the proposed task-specific end-to-end metric on the same search space as SPOS [7]. We further provide a breakup of time consumption to illustrate the computational efficiency of DSNAS.

4.1. Accuracy correlation of two-stage NAS

Since the validity of the searching in two-stage NAS relies on a high correlation in the performance of searching stage and evaluation stage, we check this assumption with a ranking correlation measure, Kendall Tau metric $\tau$ [10].

$$\tau = \frac{2(N_{\text{concordant}} - N_{\text{disconcordant}})}{N(N - 1)},$$  

where $N$ is the total number of pairs $(x_i, y_i)$ from the searching stage and evaluation stage consisting of $N_{\text{concordant}}$ concordant ranking pairs $(x_1 > x_2, y_1 > y_2)$ or $x_1 < x_2, y_1 < y_2$ and $N_{\text{disconcordant}}$ discordant ranking pairs $(x_1 > x_2, y_1 < y_2$ or $x_1 < x_2, y_1 > y_2$). Kendall Tau metric ranges from -1 to 1, which means the ranking order changes from reversed to identical. $\tau$ being close to 0 indicates the absence of correlation.

We measure the ranking correlation by calculating Kendall Tau metric from two perspectives: (1) The $\tau_{\text{inter}}$ is calculated based on the top-k model performance of the searching and evaluation stage in one single searching process; (2) The Kendall Tau metric $\tau_{\text{intra}}$ is calculated by running the two-stage NAS methods several times with different random seeds using the top-1 model performance in each searching process. As shown in Table 2, the performance correlation between the searching stage and evaluation stage in both SPOS and ProxylessNAS is fairly low. This indicates the necessity of task-specific end-to-end NAS problem formulation. Fairly low correlation may also imply reproducibility problems.

| Model               | $\tau_{\text{inter}}$ | $\tau_{\text{intra}}$ |
|---------------------|------------------------|------------------------|
| Single Path One-Shot[7] | 0.35                   | -0.07                  |
| ProxylessNas [3]    | -                      | -0.33                  |

Table 2: Kendall Tau metric $\tau$ calculated with the top-k model performance in the searching and evaluation stage. $\tau_{\text{inter}}$ measures the correlation of top-k model performance of the searching and evaluation stage in one single searching process while $\tau_{\text{intra}}$ measures the correlation of top-1 model performance from different searching processes.

4.2. Single-path architecture search

Motivation To compare the efficiency and accuracy of derived networks from DSNAS versus existing two-stage methods, we conduct experiment in single-path setting. Results are compared in the task-specific end-to-end metrics. Dataset All our experiments are conducted in a mobile setting on the ImageNet Classification task [18] with a resource constraint $FLOPS \leq 330M$. This dataset consists of around $1.28 \times 10^9$ training images and $5 \times 10^4$ validation images. Data transformation is achieved by the standard pre-processing techniques described in the supplementary material.
Figure 3. Searching process of two-stage SPOS and single-stage SPOS/DSNAS. SPOSsearch120retrain240 and SPOSsearch240retrain240 search for 120/240 epochs then retrain the derived architecture for 240 epochs. Instead of retraining, SPOSsearch120tune120 finetunes the result for 120 epochs. DSNASsearch240 and SPOSsearch240 utilize one-stage training for 240 epochs. DSNASsearch240 applies progressive early stop, SPOSsearch240 applies one-shot EA at 120th epoch.

Search Space The basic building block design is inspired by ShuffleNet v2 [15]. There are 4 candidates for each choice block in the parent network, i.e., choice_3, choice_5, choice_7, and choice_x. These candidates differ in the kernel size and the number of depthwise convolutions, spanning a search space with $2^4 \times 20$ single path models. The overall architecture of the parent network and building blocks are shown in the supplementary material.

Training Settings We follow the same setting as SPOS [7] except that we do not have an evaluation stage in our searching process. We adopt a SGD optimizer with a momentum of 0.9 [22] to update the parent network weight parameters. A cosine learning rate scheduler with an initial learning rate of 0.5 is applied. Moreover, an L2 weight decay ($4 \times 10^{-5}$) is used to regularize the training process. The architecture parameters are updated using the Adam optimizer with an initial learning rate of 0.001. All our experiments are done on 8 NVIDIA TITAN X GPUs.

Searching Process To demonstrate the efficiency of DSNAS, we compare the whole process needed to accomplish task-specific end-to-end NAS in ImageNet classification with two-stage NAS methods. Among all existing two-stage methods, SPOS [7] is the one with state-of-the-art accuracy and efficiency. SPOS can be regarded as a weight-sharing version of random search, where the search is conducted with one-shot evolution algorithm after training the uniformly sampled parent network.

Figure 3 shows DSNAS’s advantage over several different configurations of SPOS. We purposefully present curves in terms of both epoch number and time to illustrate that even though DSNAS updates architecture in an iteration-basis, almost no extra computation time is introduced. Among the four configurations of SPOS, SPOSsearch120retrain240 is the original one as in Guo et al. [7], using the two-stage paradigm. Obviously, DSNAS achieves comparable accuracy in an end-to-end manner, with roughly 34% less computational resources. As SPOSsearch120retrain240 updates block parameters for only 120 epochs, we run the SPOSsearch120tune120 and SPOSsearch240retrain240 configurations for fair comparison. At the end of the 240th epoch, the accuracy of SPOS models is around 1.4% and 4% lower than DSNAS’s respectively.

In addition, for the ablation study of DSNAS’s progressive early stop strategy, we call the EA algorithm of SPOS at the 120th epoch in the one-stage DSNASsearch240 configuration. Continuing the parameter training, the selected models experience a leap in accuracy and converge with accuracy 1.3% lower than DSNAS’s. However, seeking this EA point is fairly ad hoc and prone to random noise.

Searching Results The experimental results are reported in Table 3. Comparing with all existing two-stage NAS methods, DSNAS shows comparable performance using at least 1/3 less computational resources. More importantly, the standard deviation in DSNAS’s accuracy is lower than those from both searching and evaluation stage from EA-based SPOS (0.22 vs 0.38/0.36). This exhibits as a differentiable NAS framework, DSNAS is a more robust method in the task-specific end-to-end metric.

4.3. Time consumption breakup

In last subsection, we show DSNAS can achieve comparable performance under the task-specific end-to-end metric.
Table 3. Results of choice block search. The time is measured based on NVIDIA TITAN X and accuracy is calculated on the validation set. * is our implementation with the original paper setting. 40000§ is the GPU hour converted from 6912 TPUv2 hours with a ratio of roughly 1:6. 300‡ is the GPU hour converted from V100 GPU with a ratio of 1:1.5. 68.7† is the accuracy on the search set.

| Model                  | FLOPS  | Search | Retrain | No proxy | Time (GPU hour) |
|------------------------|--------|--------|---------|----------|-----------------|
|                        |        | Top-1  | Top-5   | Top-1    | Top-5          |                  |
|                        |        | acc(%) | acc(%)  | acc(%)   | acc(%)         |
|                        |        |        |         |          | Manual          |
| MobileNet V1 (0.75x)[8]| 325M   | Manual | 68.4    | -        | Manual          |
| MobileNet V2 (1.0x)[19]| 300M   | Manual | 72.0    | 91.00    | Manual          |
| ShuffleNet V2 (1.5x)[15]| 299M | Manual | 72.6    | 90.60    | Manual          |
| NASNET-A(4@1056)[29]  | 564M   | -      | 74.0    | 91.60    | False           |
| PNASNET[13]            | 588M   | -      | 74.2    | 91.90    | False           |
| MnasNet-A1[23]         | 312M   | -      | 75.2    | 92.50    | False           |
| DARTS[14]              | 574M   | -      | 73.3    | 91.30    | False           |
| SNAS[27]               | 522M   | -      | 72.7    | 90.80    | False           |
| Proxyless-R (mobile)[3]| 320M   | 62.6*  | 84.7*   | 74.6     | True            |
| Single Path One-Shot[7]| 319M   | 68.7†  | -       | 74.3     | True            |
| Single Path One-Shot*  | 323M   | 68.2±0.38 | 88.28   | 74.3±0.36 | True            |
| Random Search ≤330M    | ≤68.2  | ≤88.31 | ≤73.9   | ≤91.8    | True            |
| DSNAS                  | 324M   | 74.4±0.22 | 91.54   | 74.3±0.27| 91.90          | True            | 420          |

In this subsection, we further break up the time consumption of DSNAS into several specific parts, i.e. forward, backward, optimization and test, and conduct a controlled comparison with other differentiable NAS methods. We also hope such a detailed breakup can help readers gain insight into further optimizing our implementation.

We first compare the computation time of SNAS and DSNAS on CIFAR-10 dataset. The average time of each split is shown in Table 4. Under the same setting, our DSANS is almost five folds faster than SNAS and consumes only 1/n of GPU memory as SNAS (n is the total number of candidate operations in each edge).

| Method | Forward | Backward | Opt | Test |
|--------|---------|----------|-----|------|
| SNAS   | 0.26s   | 0.46s    | 0.14s | 0.18s|
| DSNAS  | 0.05s   | 0.07s    | 0.13s | 0.04s|

Table 4. Computation time of SNAS and DSNAS.

We further compare the average time of each split and ProxylessNAS in a mobile setting on the ImageNet Classification task. As shown in Table 5, the average time is calculated on the same search space of ProxylessNAS [3] with a total batch size of 512. With a fair comparison, DSNAS is roughly two folds faster than ProxylessNAS.

Table 5. Computation time of ProxylessNAS and DSNAS.

5. Summary and future work

In this work, we first define a task-specific end-to-end NAS problem, under the evaluation metrics of which we scrutinize the efficiency of two-stage NAS methods. We then propose an efficient differentiable NAS framework, DSNAS, which optimizes architecture and parameters in the same round of back-propagation. Subnetworks derived from DSNAS are ready-to-deploy. One competitive counterpart would be EfficientNet[24], which tries to bridge two stages with extra grid search on network scale after NAS. However, its total cost is larger than DSNAS. More accuracy gain can be achieved in DSNAS if scales are searched similarly. As a framework, DSNAS is orthogonal to the random wiring solution, which focuses on graph topology search [26]. We look forward to their combination for a joint search of topology, operations, and parameters.

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A. Detailed Settings of Experimental Results

Data Pre-processing We employ the commonly used pre-processing techniques in our experiments: A 224x224 crop is randomly sampled from an image or its horizontal flip, with a normalization on the pixel values per channel.

B. Details about the architectures

Structures of choice blocks

![Choice blocks with stride=1](image)

Figure 4. Choice blocks with stride=1. Choice blocks in search space. From left to right: Choice_3, Choice_5, Choice_7, Choice_x.

Structures of searched architectures

![Choice blocks with stride=2](image)

Figure 5. Choice blocks with stride=2. Choice blocks in search space. From left to right: Choice_3, Choice_5, Choice_7, Choice_x.

Supernet architecture

![Supernet architecture](image)

Table 6. Supernet architecture. CB - choice block. GAP - global average pooling. FC - fully connected layer. Each line describes a sequence of 1 or more identical layers, repeated Repeat times. All layers in the same sequence have the same number of output channels. The first layer of each sequence has a stride Stride and all others use stride 1.

| Input   | Block | Channels | Repeat | Stride |
|---------|-------|----------|--------|--------|
| 224² x 3 | 3 x 3 Conv | 16       | 1      | 2      |
| 112² x 16 | CB    | 64       | 4      | 2      |
| 56² x 64  | CB    | 160      | 4      | 2      |
| 28² x 160 | CB    | 320      | 8      | 2      |
| 14² x 320 | CB    | 640      | 4      | 2      |
| 7² x 640  | 1 x 1 Conv | 1024  | 1      | 1      |
| 7² x 1024 | GAP   | -        | 1      | -      |
| 1024      | FC    | 1000     | 1      | -      |

6We follow the setting including choice blocks used in the released implementation of SPOS[7].