

TinyTL: Reduce Activations, Not Trainable Parameters for Efficient On-Device Learning

Han Cai¹, Chuang Gan², Ligeng Zhu¹, Song Han¹

¹Massachusetts Institute of Technology, ²MIT-IBM Watson AI Lab

<http://tinyml.mit.edu/>

Abstract

On-device learning enables edge devices to continually adapt the AI models to new data, which requires a small memory footprint to fit the tight memory constraint of edge devices. Existing work solves this problem by reducing the number of trainable parameters. However, this doesn't directly translate to memory saving since the major bottleneck is the activations, not parameters. In this work, we present *Tiny-Transfer-Learning* (TinyTL) for memory-efficient on-device learning. TinyTL freezes the *weights* while only learns the *bias* modules, thus no need to store the intermediate activations. To maintain the adaptation capacity, we introduce a new memory-efficient bias module, the *lite residual module*, to refine the feature extractor by learning small residual feature maps adding only 3.8% memory overhead. Extensive experiments show that TinyTL significantly saves the memory (up to **6.5** \times) with little accuracy loss compared to fine-tuning the full network. Compared to fine-tuning the last layer, TinyTL provides significant accuracy improvements (up to **34.1%**) with little memory overhead. Furthermore, combined with feature extractor adaptation, TinyTL provides **7.3-12.9** \times memory saving without sacrificing accuracy compared to fine-tuning the full Inception-V3.

1 Introduction

Intelligent edge devices with rich sensors (e.g., billions of mobile phones and IoT devices)¹ have been ubiquitous in our daily lives. These devices keep collecting *new* and *sensitive* data through the sensor every day while being expected to provide high-quality and customized services without sacrificing privacy². These pose new challenges to efficient AI systems that could not only run inference but also continually fine-tune the pre-trained models on newly collected data (i.e., on-device learning).

Though on-device learning can enable many appealing applications, it is an extremely challenging problem. First, edge devices are *memory-constrained*. For example, a Raspberry Pi 1 Model A only has 256MB of memory, which is sufficient for inference, but by far insufficient for training (Figure 1 left), even using a lightweight neural network architecture (MobileNetV2 [1]). Furthermore, the memory is shared by various on-device applications (e.g., other deep learning models) and the operating system. A single application may only be allocated a small fraction of the total memory, which makes this challenge more critical. Second, edge devices are *energy-constrained*. DRAM access consumes two orders of magnitude more energy than on-chip SRAM access. The large memory footprint of activations cannot fit into the limited on-chip SRAM, thus has to access DRAM. For instance, the training memory of MobileNetV2, under batch size 16, is close to 1GB, which is by far larger than the SRAM size of an AMD EPYC CPU³ (Figure 1 left), not to mention lower-end

¹<https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/>

²https://ec.europa.eu/info/law/law-topic/data-protection_en

³<https://www.amd.com/en/products/cpu/amd-epyc-7302>

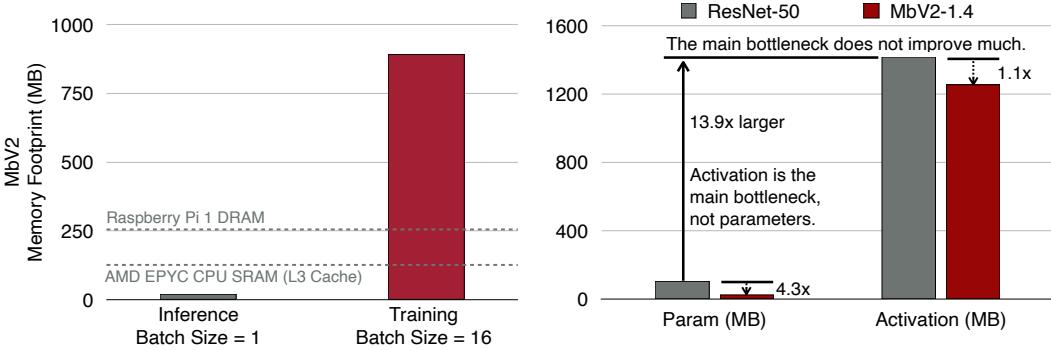


Figure 1: *Left*: The memory footprint required by training is much larger than inference. *Right*: Memory cost comparison between ResNet-50 and MobileNetV2-1.4 under batch size 16. Recent advances in efficient model design only reduce the size of parameters, but the activation size, which is the main bottleneck for training, does not improve much.

edge platforms. If the training memory can fit on-chip SRAM, it will drastically improve the speed and energy efficiency.

There is plenty of efficient inference techniques that reduce the number of trainable parameters and the computation FLOPs [1, 2, 3, 4, 5, 6, 7, 8, 9, 10], however, parameter-efficient or FLOPs-efficient techniques do not directly save the training memory. It is the activation that bottlenecks the training memory, not the parameters. For example, Figure 1 (right) compares ResNet-50 and MobileNetV2-1.4. In terms of parameter size, MobileNetV2-1.4 is 4.3 \times smaller than ResNet-50. However, for training activation size, MobileNetV2-1.4 is almost the same as ResNet-50 (only 1.1 \times smaller), leading to little memory reduction. It is essential to reduce the size of intermediate activations required by back-propagation, which is the key memory bottleneck for efficient on-device training.

In this paper, we propose *Tiny-Transfer-Learning* (TinyTL) to address these challenges. By analyzing the memory footprint during the backward pass, we notice that the intermediate activations (the main bottleneck) are only needed when updating the weights, not the biases (Eq. 2). Inspired by this finding, we propose to freeze the weights of the pre-trained feature extractor and only update the biases to reduce the memory footprint (Figure 2b). To compensate for the capacity loss, we introduce a memory-efficient bias module, called *lite residual module*, which improves the model capacity by refining the intermediate feature maps of the feature extractor (Figure 2c). Meanwhile, we aggressively shrink the resolution and width of the lite residual module to have a small memory overhead (only 3.8%). Extensive experiments on 9 image classification datasets with the same pre-trained model (ProxylessNAS-Mobile [11]) demonstrate the effectiveness of TinyTL compared to previous transfer learning methods. Further, combined with a pre-trained once-for-all network [10], TinyTL can select a specialized sub-network as the feature extractor for each transfer dataset (i.e., feature extractor adaptation): given a more difficult dataset, a larger sub-network is selected, and vice versa. TinyTL achieves the same level of (or even higher) accuracy compared to fine-tuning the full Inception-V3 while reducing the training memory footprint by up to 12.9 \times . Our contributions can be summarized as follows:

- We propose TinyTL, a novel transfer learning method to reduce the training memory footprint by an order of magnitude for efficient on-device learning. We systematically analyze the memory of training and find the bottleneck comes from updating the weights, not biases (assume ReLU activation).
- We also introduce the *lite residual module*, a memory-efficient bias module to improve the model capacity with little memory overhead.
- Extensive experiments on transfer learning tasks show that our method is highly memory-efficient and effective. It reduces the training memory footprint by up to 12.9 \times without sacrificing accuracy.

2 Related Work

Efficient Inference Techniques. Improving the inference efficiency of deep neural networks on resource-constrained edge devices has recently drawn extensive attention. Starting from [4, 5, 12, 13,

[14], one line of research focuses on compressing pre-trained neural networks, including i) network pruning that removes less-important units [4, 15] or channels [16, 17]; ii) network quantization that reduces the bitwidth of parameters [5, 18] or activations [19, 20]. However, these techniques cannot handle the training phase, as they rely on a well-trained model on the target task as the starting point.

Another line of research focuses on lightweight neural architectures by either manual design [1, 2, 3, 21, 22] or neural architecture search [6, 8, 11, 23]. These lightweight neural networks provide highly competitive accuracy [10, 24] while significantly improving inference efficiency. However, concerning the training memory efficiency, key bottlenecks are not solved: **the training memory is dominated by activations, not parameters** (Figure 1).

There are also some non-deep learning methods [25, 26, 27] that are designed for efficient inference on edge devices. These methods are suitable for handling simple tasks like MNIST. However, for more complicated tasks, we still need the representation capacity of deep neural networks.

Memory Footprint Reduction. Researchers have been seeking ways to reduce the training memory footprint. One typical approach is to re-compute discarded activations during backward [28, 29]. This approach reduces memory usage at the cost of a large computation overhead. Thus it is not preferred for edge devices. Layer-wise training [30] can also reduce the memory footprint compared to end-to-end training. However, it cannot achieve the same level of accuracy as end-to-end training. Another representative approach is through activation pruning [31], which builds a dynamic sparse computation graph to prune activations during training. Similarly, [32] proposes to reduce the bitwidth of training activations by introducing new reduced-precision floating-point formats. Besides reducing the training memory cost, there are some techniques that focus on reducing the peak inference memory cost, such as RNNPool [33] and MemNet [34]. Our method is orthogonal to these techniques and can be combined to further reduce the memory footprint.

Transfer Learning. Neural networks pre-trained on large-scale datasets (e.g., ImageNet [35]) are widely used as a fixed feature extractor for transfer learning, then only the last layer needs to be fine-tuned [36, 37, 38, 39]. This approach does not require to store the intermediate activations of the feature extractor, and thus is memory-efficient. However, the capacity of this approach is limited, resulting in poor accuracy, especially on datasets [40, 41] whose distribution is far from ImageNet (e.g., only 45.9% Aircraft top1 accuracy achieved by Inception-V3 [42]). Alternatively, fine-tuning the full network can achieve better accuracy [43, 44]. But it requires a vast memory footprint and hence is not friendly for training on edge devices. Recently, [45, 46] propose to only update parameters of the batch normalization (BN) [47] layers, which greatly reduces the number of trainable parameters. **Unfortunately, parameter-efficiency doesn't translate to memory-efficiency.** It still requires a large amount of memory (e.g., 326MB under batch size 8) to store the input activations of the BN layers (Table 3). Additionally, the accuracy of this approach is still much worse than fine-tuning the full network (70.7% v.s. 85.5%; Table 3). People can also partially fine-tune some layers, but how many layers to select is still ad hoc. This paper provides a systematic approach to save memory without losing accuracy.

3 Tiny Transfer Learning

3.1 Understanding the Memory Footprint of Back-propagation

Without loss of generality, we consider a neural network \mathcal{M} that consists of a sequence of layers:

$$\mathcal{M}(\cdot) = \mathcal{F}_{\mathbf{w}_n}(\mathcal{F}_{\mathbf{w}_{n-1}}(\cdots \mathcal{F}_{\mathbf{w}_2}(\mathcal{F}_{\mathbf{w}_1}(\cdot)) \cdots)), \quad (1)$$

where \mathbf{w}_i denotes the parameters of the i^{th} layer. Let \mathbf{a}_i and \mathbf{a}_{i+1} be the input and output activations of the i^{th} layer, respectively, and \mathcal{L} be the loss. In the backward pass, given $\frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}}$, there are two goals for the i^{th} layer: computing $\frac{\partial \mathcal{L}}{\partial \mathbf{a}_i}$ and $\frac{\partial \mathcal{L}}{\partial \mathbf{w}_i}$.

Assuming the i^{th} layer is a linear layer whose forward process is given as: $\mathbf{a}_{i+1} = \mathbf{a}_i \mathbf{W} + \mathbf{b}$, then its backward process under batch size 1 is

$$\frac{\partial \mathcal{L}}{\partial \mathbf{a}_i} = \frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}} \frac{\partial \mathbf{a}_{i+1}}{\partial \mathbf{a}_i} = \frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}} \mathbf{W}^T, \quad \frac{\partial \mathcal{L}}{\partial \mathbf{W}} = \mathbf{a}_i^T \frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}}, \quad \frac{\partial \mathcal{L}}{\partial \mathbf{b}} = \frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}}. \quad (2)$$

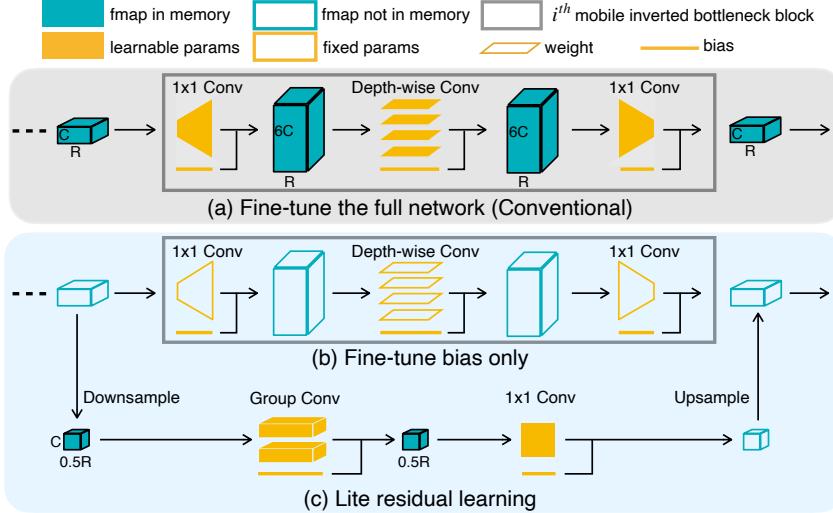


Figure 2: TinyTL overview (“C” denotes the width and “R” denote the resolution). Conventional transfer learning relies on fine-tuning the weights to adapt the model (Fig.a), which requires a large amount of activation memory (in blue) for back-propagation. TinyTL reduces the memory usage by fixing the weights (Fig.b) while only fine-tuning the bias. (Fig.c) exploit *lite residual learning* to compensate for the capacity loss, using group convolution and avoiding inverted bottleneck to achieve high arithmetic intensity and small memory footprint. The skip connection remains unchanged (omitted for simplicity).

According to Eq. (2), the intermediate activations (i.e., $\{\mathbf{a}_i\}$) that dominate the memory footprint are only required to compute the gradient of the weights (i.e., $\frac{\partial \mathcal{L}}{\partial \mathbf{W}}$), not the bias. If we only update the bias, training memory can be greatly saved. This property is also applicable to convolution layers and normalization layers (e.g., batch normalization [47], group normalization [48], etc) since they can be considered as special types of linear layers.

Regarding non-linear activation layers (e.g., ReLU, sigmoid, h-swish), sigmoid and h-swish require to store \mathbf{a}_i to compute $\frac{\partial \mathcal{L}}{\partial \mathbf{a}_i}$ (Table 1), hence they are not memory-efficient. Activation layers that build upon them are also not memory-efficient consequently, such as tanh, swish [49], etc. In contrast, ReLU and other ReLU-styled activation layers (e.g., LeakyReLU [50]) only requires to store a binary mask representing whether the value is smaller than 0, which is $32\times$ smaller than storing \mathbf{a}_i .

Table 1: Detailed forward and backward processes of non-linear activation layers. $|\mathbf{a}_i|$ denotes the number of elements of \mathbf{a}_i . “ \circ ” denotes the element-wise product. $(\mathbf{1}_{\mathbf{a}_i \geq 0})_j = 0$ if $(\mathbf{a}_i)_j < 0$ and $(\mathbf{1}_{\mathbf{a}_i \geq 0})_j = 1$ otherwise. $\text{ReLU6}(\mathbf{a}_i) = \min(6, \max(0, \mathbf{a}_i))$.

Layer Type	Forward	Backward	Memory Cost
ReLU	$\mathbf{a}_{i+1} = \max(0, \mathbf{a}_i)$	$\frac{\partial \mathcal{L}}{\partial \mathbf{a}_i} = \frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}} \circ \mathbf{1}_{\mathbf{a}_i \geq 0}$	$ \mathbf{a}_i $ bits
sigmoid	$\mathbf{a}_{i+1} = \sigma(\mathbf{a}_i) = \frac{1}{1+\exp(-\mathbf{a}_i)}$	$\frac{\partial \mathcal{L}}{\partial \mathbf{a}_i} = \frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}} \circ \sigma(\mathbf{a}_i) \circ (1 - \sigma(\mathbf{a}_i))$	$32 \mathbf{a}_i $ bits
h-swish [7]	$\mathbf{a}_{i+1} = \mathbf{a}_i \circ \frac{\text{ReLU6}(\mathbf{a}_i + 3)}{6}$	$\frac{\partial \mathcal{L}}{\partial \mathbf{a}_i} = \frac{\partial \mathcal{L}}{\partial \mathbf{a}_{i+1}} \circ \left(\frac{\text{ReLU6}(\mathbf{a}_i + 3)}{6} + \mathbf{a}_i \circ \frac{1_{-3 \leq \mathbf{a}_i \leq 3}}{6} \right)$	$32 \mathbf{a}_i $ bits

3.2 Lite Residual Learning

Based on the memory footprint analysis, one possible solution of reducing the memory cost is to freeze the weights of the pre-trained feature extractor while only update the biases (Figure 2b). However, only updating biases has limited adaptation capacity. Therefore, we introduce lite residual learning that exploits a new class of generalized memory-efficient bias modules to refine the intermediate feature maps (Figure 2c).

Formally, a layer with frozen weights and learnable biases can be represented as:

$$\mathbf{a}_{i+1} = \mathcal{F}_W(\mathbf{a}_i) + \mathbf{b}. \quad (3)$$

To improve the model capacity while keeping a small memory footprint, we propose to add a lite residual module that generates a residual feature map to refine the output:

$$\mathbf{a}_{i+1} = \mathcal{F}_W(\mathbf{a}_i) + \mathbf{b} + \mathcal{F}_{W_r}(\mathbf{a}'_i = \text{reduce}(\mathbf{a}_i)), \quad (4)$$

where $\mathbf{a}'_i = \text{reduce}(\mathbf{a}_i)$ is the reduced activation. According to Eq. (2), learning these lite residual modules only requires to store the reduced activations $\{\mathbf{a}'_i\}$ rather than the full activations $\{\mathbf{a}_i\}$.

Implementation (Figure 2c). We apply Eq. (4) to mobile inverted bottleneck blocks (MB-block) [1]. The key principle is to keep the activation small. Following this principle, we explore two design dimensions to reduce the activation size:

- **Width.** The widely-used inverted bottleneck requires a huge number of channels ($6\times$) to compensate for the small capacity of a depthwise convolution, which is parameter-efficient but highly activation-inefficient. Even worse, converting $1\times$ channels to $6\times$ channels back and forth requires two 1×1 projection layers, which doubles the total activation to $12\times$. Depthwise convolution also has a very low arithmetic intensity (its OPs/Byte is less than 4% of 1×1 convolution’s OPs/Byte if with 256 channels), thus highly memory in-efficient with little reuse. To solve these limitations, our lite residual module employs the group convolution that has much higher arithmetic intensity than depthwise convolution, providing a good trade-off between FLOPs and memory. That also removes the 1×1 projection layer, reducing the total channel number by $\frac{6\times 2+1}{1+1} = 6.5\times$.
- **Resolution.** The activation size grows quadratically with the resolution. Therefore, we shrink the resolution in the lite residual module by employing a 2×2 average pooling to downsample the input feature map. The output of the lite residual module is then upsampled to match the size of the main branch’s output feature map via bilinear upsampling. Combining resolution and width optimizations, the activation of our lite residual module is roughly $2^2 \times 6.5 = 26\times$ smaller than the inverted bottleneck.

3.3 Discussions

Normalization Layers. As discussed in Section 3.1, TinyTL flexibly supports different normalization layers, including batch normalization (BN), group normalization (GN), layer normalization (LN), and so on. In particular, BN is the most widely used one in vision tasks. However, BN requires a large batch size to have accurate running statistics estimation during training, which is not suitable for on-device learning where we want a small training batch size to reduce the memory footprint. Moreover, the data may come in a streaming fashion in on-device learning, which requires a training batch size of 1. In contrast to BN, GN can handle a small training batch size as the running statistics in GN are computed independently for different inputs. In our experiments, GN with a small training batch size (e.g., 8) performs slightly worse than BN with a large training batch size (e.g., 256). However, as we target at on-device learning, we choose GN in our models.

Feature Extractor Adaptation. TinyTL can be applied to different backbone neural networks, such as MobileNetV2 [1], ProxylessNASNets [11], EfficientNets [24], etc. However, since the weights of the feature extractor are frozen in TinyTL, we find using the same backbone neural network for all transfer tasks is sub-optimal. Therefore, we choose the backbone of TinyTL using a pre-trained once-for-all network [10] to adaptively select the specialized feature extractor that best fits the target transfer dataset. Specifically, a once-for-all network is a special kind of neural network that is sparsely activated, from which many different sub-networks can be derived without retraining by sparsely activating parts of the model according to the architecture configuration (i.e., depth, width, kernel size, resolution), while the weights are shared. This allows us to efficiently evaluate the effectiveness of a backbone neural network on the target transfer dataset without the expensive pre-training process. Further details of the feature extractor adaptation process are provided in Appendix A.

Table 2: Comparison between TinyTL and conventional transfer learning methods (training memory footprint is calculated assuming the batch size is 8 and the classifier head for Flowers is used). For object classification datasets, we report the top1 accuracy (%) while for CelebA we report the average top1 accuracy (%) over 40 facial attribute classification tasks. ‘B’ represents Bias while ‘L’ represents LiteResidual. *FT-Last* represents only the last layer is fine-tuned. *FT-Norm+Last* represents normalization layers and the last layer are fine-tuned. *FT-Full* represents the full network is fine-tuned. The backbone neural network is ProxylessNAS-Mobile, and the resolution is 224 except for ‘TinyTL-L+B@320’ whose resolution is 320. TinyTL consistently outperforms *FT-Last* and *FT-Norm+Last* by a large margin with a similar or lower training memory footprint. By increasing the resolution to 320, TinyTL can reach the same level of accuracy as *FT-Full* while being $6\times$ memory efficient.

Method	Train-Mem.	Flowers	Cars	CUB	Food	Pets	Aircraft	CIFAR10	CIFAR100	CelebA
FT-Last	31MB	90.1	50.9	73.3	68.7	91.3	44.9	85.9	68.8	88.7
TinyTL-B	32MB	93.5	73.4	75.3	75.5	92.1	63.2	93.7	78.8	90.4
TinyTL-L	37MB	95.3	84.2	76.8	79.2	91.7	76.4	96.1	80.9	91.2
TinyTL-L+B	37MB	95.5	85.0	77.1	79.7	91.8	75.4	95.9	81.4	91.2
TinyTL-L+B@320	65MB	96.8	88.8	81.0	82.9	92.9	82.3	96.1	81.5	-
FT-Norm+Last	192MB	94.3	77.9	76.3	77.0	92.2	68.1	94.8	80.2	90.4
FT-Full	391MB	96.8	90.2	81.0	84.6	93.0	86.0	97.1	84.1	91.4

4 Experiments

4.1 Setups

Datasets. Following the common practice [43, 44, 45], we use ImageNet [35] as the pre-training dataset, and then transfer the models to 8 downstream object classification tasks, including Cars [41], Flowers [51], Aircraft [40], CUB [52], Pets [53], Food [54], CIFAR10 [55], and CIFAR100 [55]. Besides object classification, we also evaluate our TinyTL on human facial attribute classification tasks, where CelebA [56] is the transfer dataset and VGGFace2 [57] is the pre-training dataset.

Model Architecture. To justify the effectiveness of TinyTL, we first apply TinyTL and previous transfer learning methods to the same backbone neural network, ProxylessNAS-Mobile [11]. For each MB-block in ProxylessNAS-Mobile, we insert a lite residual module as described in Section 3.2 and Figure 2 (c). The group number is 2, and the kernel size is 5. We use the ReLU activation since it is more memory-efficient according to Section 3.1. We replace all BN layers with GN layers to better support small training batch sizes. We set the number of channels per group to 8 for all GN layers. Following [58], we apply weight standardization [59] to convolution layers that are followed by GN.

For feature extractor adaptation, we build the once-for-all network using the MobileNetV2 design space [10, 11] that contains five stages with a gradually decreased resolution, and each stage consists of a sequence of MB-blocks. In the stage-level, it supports elastic depth (i.e., 2, 3, 4). In the block-level, it supports elastic kernel size (i.e., 3, 5, 7) and elastic width expansion ratio (i.e., 3, 4, 6). Similarly, for each MB-block in the once-for-all network, we insert a lite residual module that supports elastic group number (i.e., 2, 4) and elastic kernel size (i.e., 3, 5).

Training Details. We freeze the memory-heavy modules (weights of the feature extractor) and only update memory-efficient modules (bias, lite residual, classifier head) during transfer learning. The models are fine-tuned for 50 epochs using the Adam optimizer [60] with batch size 8 on a single GPU. The initial learning rate is tuned for each dataset while cosine schedule [61] is adopted for learning rate decay. We apply 8bits weight quantization [5] on the frozen weights to reduce the parameter size, which causes a negligible accuracy drop in our experiments. For all compared methods, we also assume the 8bits weight quantization is applied if eligible when calculating their training memory footprint. Additionally, as PyTorch does not support explicit fine-grained memory management, we use the theoretically calculated training memory footprint for comparison in our experiments. For simplicity, we assume the batch size is 8 for all compared methods throughout the experiment section.

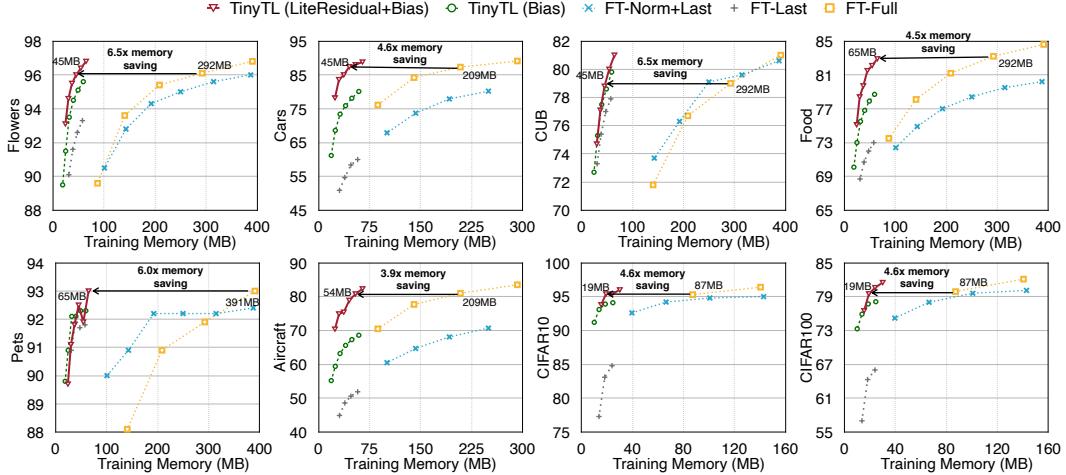


Figure 3: Top1 accuracy results of different transfer learning methods under varied resolutions using the same pre-trained neural network (ProxylessNAS-Mobile). With the same level of accuracy, TinyTL achieves 3.9-6.5 \times memory saving compared to fine-tuning the full network.

4.2 Main Results

Effectiveness of TinyTL. Table 2 reports the comparison between TinyTL and previous transfer learning methods including: i) fine-tuning the last linear layer [36, 37, 39] (referred to as *FT-Last*); ii) fine-tuning the normalization layers (e.g., BN, GN) and the last linear layer [42] (referred to as *FT-Norm+Last*) ; iii) fine-tuning the full network [43, 44] (referred to as *FT-Full*). We also study several variants of TinyTL including: i) TinyTL-B that fine-tunes biases and the last linear layer; ii) TinyTL-L that fine-tunes lite residual modules and the last linear layer; iii) TinyTL-L+B that fine-tunes lite residual modules, biases, and the last linear layer. All compared methods use the same pre-trained model but fine-tune different parts of the model as discussed above. We report the average accuracy across five runs.

Compared to *FT-Last*, TinyTL maintains a similar training memory footprint while improving the top1 accuracy by a significant margin. In particular, TinyTL-L+B improves the top1 accuracy by **34.1%** on Cars, by **30.5%** on Aircraft, by **12.6%** on CIFAR100, by **11.0%** on Food, etc. It shows the improved adaptation capacity of our method over *FT-Last*. Compared to *FT-Norm+Last*, TinyTL-L+B improves the training memory efficiency by **5.2 \times** while providing up to **7.3%** higher top1 accuracy, which shows that our method is not only more memory-efficient but also more effective than *FT-Norm+Last*. Compared to *FT-Full*, TinyTL-L+B@320 can achieve the same level of accuracy while providing **6.0 \times** training memory saving.

Regarding the comparison between different variants of TinyTL, both TinyTL-L and TinyTL-L+B have clearly better accuracy than TinyTL-B while incurring little memory overhead. It shows that the lite residual modules are essential in TinyTL. Besides, we find that TinyTL-L+B is slightly better than TinyTL-L on most of the datasets while maintaining the same memory footprint. Therefore, we choose TinyTL-L+B as the default.

Figure 3 demonstrates the results under different input resolutions. We can observe that simply reducing the input resolution will result in significant accuracy drops for *FT-Full*. In contrast, TinyTL can reduce the memory footprint by **3.9-6.5 \times** while having the same or even higher accuracy compared to fine-tuning the full network.

Combining TinyTL and Feature Extractor Adaptation. Table 3 summarizes the results of TinyTL and previously reported transfer learning results, where different backbone neural networks are used as the feature extractor. Combined with feature extractor adaptation, TinyTL achieves **7.5-12.9 \times** memory saving compared to fine-tuning the full Inception-V3, reducing from 850MB to 66-114MB while providing the same level of accuracy. Additionally, we try updating the last two layers besides biases and lite residual modules (indicated by \dagger), which results in 2MB of extra

Table 3: Comparison with previous transfer learning results under different backbone neural networks. ‘I-V3’ is Inception-V3; ‘N-A’ is NASNet-A Mobile; ‘M2-1.4’ is MobileNetV2-1.4; ‘R-50’ is ResNet-50; ‘PM’ is ProxylessNAS-Mobile; ‘FA’ represents feature extractor adaptation. \dagger indicates the last two layers are updated besides biases and lite residual modules in TinyTL. TinyTL+FA reduces the training memory by **7.5-12.9 \times** without sacrificing accuracy compared to fine-tuning the widely used Inception-V3.

Method	Net	Train. mem.	Reduce ratio	Flowers	Cars	CUB	Food	Pets	Aircraft	CIFAR10	CIFAR100
FT-Full	I-V3 [44]	850MB	1.0 \times	96.3	91.3	82.8	88.7	-	85.5	-	-
	R-50 [43]	802MB	1.1 \times	97.5	91.7	-	87.8	92.5	86.6	96.8	84.5
	M2-1.4 [43]	644MB	1.3 \times	97.5	91.8	-	87.7	91.0	86.8	96.1	82.5
	N-A [43]	566MB	1.5 \times	96.8	88.5	-	85.5	89.4	72.8	96.8	83.9
FT-Norm+Last	I-V3 [42]	326MB	2.6 \times	90.4	81.0	-	-	-	70.7	-	-
FT-Last	I-V3 [42]	94MB	9.0 \times	84.5	55.0	-	-	-	45.9	-	-
TinyTL	PM@320	65MB	13.1\times	96.8	88.8	81.0	82.9	92.9	82.3	96.1	81.5
	FA@256	66MB	12.9\times	96.8	89.6	80.8	83.4	93.0	82.4	96.8	82.7
	FA@352	114MB	7.5 \times	97.4	90.7	82.4	85.0	93.4	84.8	-	-
	FA@352 \dagger	116MB	7.3 \times	-	91.5	-	86.0	-	85.4	-	-

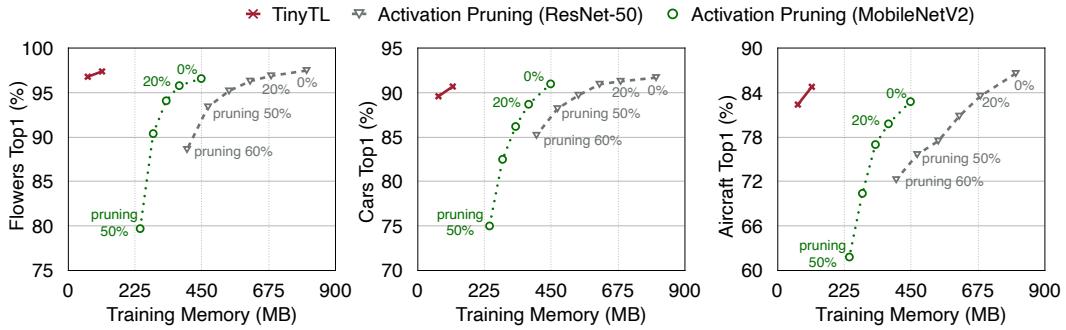


Figure 4: Compared with the dynamic activation pruning [31], TinyTL saves the memory more effectively.

training memory footprint. This slightly improves the accuracy performances, from 90.7% to 91.5% on Cars, from 85.0% to 86.0% on Food, and from 84.8% to 85.4% on Aircraft.

4.3 Ablation Studies and Discussions

Comparison with Dynamic Activation Pruning. The comparison between TinyTL and dynamic activation pruning [31] is summarized in Figure 4. TinyTL is more effective because it re-designed the transfer learning framework (lite residual module, feature extractor adaptation) rather than prune an existing architecture. The transfer accuracy drops quickly when the pruning ratio increases beyond 50% (only 2 \times memory saving). In contrast, TinyTL can achieve much higher memory reduction without loss of accuracy.

Initialization for Lite Residual Modules. By default, we use the pre-trained weights on the pre-training dataset to initialize the lite residual modules. It requires to have lite residual modules during both the pre-training phase and transfer learning phase. When applying TinyTL to existing pre-trained neural networks that do not have lite residual modules during the pre-training phase, we need to use another initialization strategy for the lite residual modules during transfer learning. To verify the effectiveness of TinyTL under this setting, we also evaluate the performances of TinyTL when using random weights [62] to initialize the lite residual modules except for the scaling parameter of the final normalization layer in each lite residual module. These scaling parameters are initialized with zeros.

Table 4 reports the summarized results. We find using the pre-trained weights to initialize the lite residual modules consistently outperforms using random weights. Besides, we also find that using

Table 4: Results of TinyTL under different initialization strategies for lite residual modules. TinyTL-L+B adds lite residual modules starting from the pre-training phase and uses the pre-trained weights to initialize the lite residual modules during transfer learning. In contrast, TinyTL-RandomL+B uses random weights to initialize the lite residual modules. Using random weights for initialization hurts the performances of TinyTL. But on datasets whose distribution is far from the pre-training dataset, TinyTL-RandomL+B still provides competitive results.

Method	Train. Mem.	Flowers	Cars	CUB	Food	Pets	Aircraft	CIFAR10	CIFAR100	CelebA
FT-Last	31MB	90.1	50.9	73.3	68.7	91.3	44.9	85.9	68.8	88.7
TinyTL-RandomL+B	37MB	88.0	82.4	72.9	79.3	84.3	73.6	95.7	81.4	91.2
TinyTL-L+B	37MB	95.5	85.0	77.1	79.7	91.8	75.4	95.9	81.4	91.2
FT-Norm+Last	192MB	94.3	77.9	76.3	77.0	92.2	68.1	94.8	80.2	90.4
FT-Full	391MB	96.8	90.2	81.0	84.6	93.0	86.0	97.1	84.1	91.4

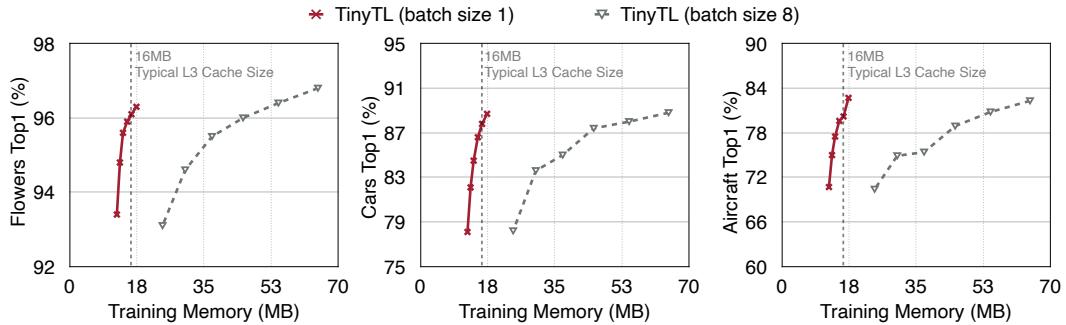


Figure 5: Results of TinyTL when trained with batch size 1. It further reduces the training memory footprint to around 16MB (typical L3 cache size), making it possible to train on the cache (SRAM) instead of DRAM.

TinyTL-RandomL+B still provides highly competitive results on Cars, Food, Aircraft, CIFAR10, CIFAR100, and CelebA. Therefore, if having the budget, it is better to use pre-trained weights to initialize the lite residual modules. If not, TinyTL can still be applied and provides competitive results on datasets whose distribution is far from the pre-training dataset.

Results of TinyTL under Batch Size 1. Figure 5 demonstrates the results of TinyTL when using a training batch size of 1. We tune the initial learning rate for each dataset while keeping the other training settings unchanged. As our model employs group normalization rather than batch normalization (Section 3.3), we observe little/no loss of accuracy than training with batch size 8. Meanwhile, the training memory footprint is further reduced to around 16MB, a typical L3 cache size. This makes it much easier to train on the cache (SRAM), which can greatly reduce energy consumption than DRAM training.

5 Conclusion

We proposed Tiny-Transfer-Learning (TinyTL) for memory-efficient on-device learning that aims to adapt pre-trained models to newly collected data on edge devices. Unlike previous methods that focus on reducing the number of parameters or FLOPs, TinyTL directly optimizes the training memory footprint by fixing the memory-heavy modules (i.e., weights) while learning memory-efficient bias modules. We further introduce lite residual modules that significantly improve the adaptation capacity of the model with little memory overhead. Extensive experiments on benchmark datasets consistently show the effectiveness and memory-efficiency of TinyTL, paving the way for efficient on-device machine learning.

Broader Impact

The proposed efficient on-device learning technique greatly reduces the training memory footprint of deep neural networks, enabling adapting pre-trained models to new data locally on edge devices without leaking them to the cloud. It can democratize AI to people in the rural areas where the Internet is unavailable or the network condition is poor. They can not only inference but also fine-tune AI models on their local devices without connections to the cloud servers. This can also benefit privacy-sensitive AI applications, such as health care, smart home, and so on.

Acknowledgements

We thank MIT-IBM Watson AI Lab, NSF CAREER Award #1943349 and NSF Award #2028888 for supporting this research. We thank MIT Satori cluster for providing the computation resource.

References

- [1] Mark Sandler, Andrew Howard, Menglong Zhu, Andrey Zhmoginov, and Liang-Chieh Chen. Mobilenetv2: Inverted residuals and linear bottlenecks. In *CVPR*, 2018. [1](#), [2](#), [3](#), [5](#)
- [2] 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 preprint arXiv:1704.04861*, 2017. [2](#), [3](#)
- [3] Xiangyu Zhang, Xinyu Zhou, Mengxiao Lin, and Jian Sun. Shufflenet: An extremely efficient convolutional neural network for mobile devices. In *CVPR*, 2018. [2](#), [3](#)
- [4] Song Han, Jeff Pool, John Tran, and William Dally. Learning both weights and connections for efficient neural network. In *NeurIPS*, 2015. [2](#), [3](#)
- [5] Song Han, Huizi Mao, and William J Dally. Deep compression: Compressing deep neural networks with pruning, trained quantization and huffman coding. In *ICLR*, 2016. [2](#), [3](#), [6](#)
- [6] 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*, 2019. [2](#), [3](#)
- [7] Andrew Howard, Mark Sandler, Grace Chu, Liang-Chieh Chen, Bo Chen, Mingxing Tan, Weijun Wang, Yukun Zhu, Ruoming Pang, Vijay Vasudevan, et al. Searching for mobilenetv3. In *ICCV*, 2019. [2](#), [4](#)
- [8] 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*, 2019. [2](#), [3](#)
- [9] Han Cai, Ji Lin, Yujun Lin, Zhijian Liu, Kuan Wang, Tianzhe Wang, Ligeng Zhu, and Song Han. Automl for architecting efficient and specialized neural networks. *IEEE Micro*, 2019. [2](#)
- [10] Han Cai, Chuang Gan, Tianzhe Wang, Zhekai Zhang, and Song Han. Once for all: Train one network and specialize it for efficient deployment. In *ICLR*, 2020. [2](#), [3](#), [5](#), [6](#), [13](#)
- [11] Han Cai, Ligeng Zhu, and Song Han. ProxylessNAS: Direct neural architecture search on target task and hardware. In *ICLR*, 2019. [2](#), [3](#), [5](#), [6](#)
- [12] Yunchao Gong, Liu Liu, Ming Yang, and Lubomir Bourdev. Compressing deep convolutional networks using vector quantization. *arXiv preprint arXiv:1412.6115*, 2014. [2](#)
- [13] Emily L Denton, Wojciech Zaremba, Joan Bruna, Yann LeCun, and Rob Fergus. Exploiting linear structure within convolutional networks for efficient evaluation. In *NeurIPS*, 2014. [2](#)
- [14] Vincent Vanhoucke, Andrew Senior, and Mark Z Mao. Improving the speed of neural networks on cpus. In *NeurIPS Deep Learning and Unsupervised Feature Learning Workshop*, 2011. [2](#)
- [15] Jonathan Frankle and Michael Carbin. The lottery ticket hypothesis: Finding sparse, trainable neural networks. In *ICLR*, 2019. [3](#)
- [16] Zhuang Liu, Jianguo Li, Zhiqiang Shen, Gao Huang, Shoumeng Yan, and Changshui Zhang. Learning efficient convolutional networks through network slimming. In *ICCV*, 2017. [3](#)

- [17] Yihui He, Xiangyu Zhang, and Jian Sun. Channel pruning for accelerating very deep neural networks. In *ICCV*, 2017. 3
- [18] Matthieu Courbariaux, Yoshua Bengio, and Jean-Pierre David. Binaryconnect: Training deep neural networks with binary weights during propagations. In *NeurIPS*, 2015. 3
- [19] Benoit Jacob, Skirmantas Kligys, Bo Chen, Menglong Zhu, Matthew Tang, Andrew Howard, Hartwig Adam, and Dmitry Kalenichenko. Quantization and training of neural networks for efficient integer-arithmetic-only inference. In *CVPR*, 2018. 3
- [20] Kuan Wang, Zhijian Liu, Yujun Lin, Ji Lin, and Song Han. Haq: Hardware-aware automated quantization. In *CVPR*, 2019. 3
- [21] Forrest N Iandola, Song Han, Matthew W Moskewicz, Khalid Ashraf, William J Dally, and Kurt Keutzer. SqueezeNet: Alexnet-level accuracy with 50x fewer parameters and< 0.5 mb model size. *arXiv preprint arXiv:1602.07360*, 2016. 3
- [22] Gao Huang, Shichen Liu, Laurens Van der Maaten, and Kilian Q Weinberger. Condensenet: An efficient densenet using learned group convolutions. In *CVPR*, 2018. 3
- [23] Han Cai, Tianyao Chen, Weinan Zhang, Yong Yu, and Jun Wang. Efficient architecture search by network transformation. In *AAAI*, 2018. 3
- [24] Mingxing Tan and Quoc Le. Efficientnet: Rethinking model scaling for convolutional neural networks. In *ICML*, 2019. 3, 5
- [25] Ashish Kumar, Saurabh Goyal, and Manik Varma. Resource-efficient machine learning in 2 kb ram for the internet of things. In *ICML*, 2017. 3
- [26] Chirag Gupta, Arun Sai Suggala, Ankit Goyal, Harsha Vardhan Simhadri, Bhargavi Paranjape, Ashish Kumar, Saurabh Goyal, Raghavendra Udupa, Manik Varma, and Prateek Jain. Protonn: Compressed and accurate knn for resource-scarce devices. In *ICML*, 2017. 3
- [27] Dennis, Don Kurian and Gaurkar, Yash and Gopinath, Sridhar and Goyal, Sachin and Gupta, Chirag and Jain, Moksh and Kumar, Ashish and Kusupati, Aditya and Lovett, Chris and Patil, Shishir G and Saha, Oindrila and Simhadri, Harsha Vardhan. EdgeML: Machine Learning for resource-constrained edge devices. 3
- [28] Audrunas Gruslys, Rémi Munos, Ivo Danihelka, Marc Lanctot, and Alex Graves. Memory-efficient backpropagation through time. In *NeurIPS*, 2016. 3
- [29] Tianqi Chen, Bing Xu, Chiyuan Zhang, and Carlos Guestrin. Training deep nets with sublinear memory cost. *arXiv preprint arXiv:1604.06174*, 2016. 3
- [30] Klaus Greff, Rupesh K Srivastava, and Jürgen Schmidhuber. Highway and residual networks learn unrolled iterative estimation. *arXiv preprint arXiv:1612.07771*, 2016. 3
- [31] Liu Liu, Lei Deng, Xing Hu, Maohua Zhu, Guoqi Li, Yufei Ding, and Yuan Xie. Dynamic sparse graph for efficient deep learning. In *ICLR*, 2019. 3, 8
- [32] Naigang Wang, Jungwook Choi, Daniel Brand, Chia-Yu Chen, and Kailash Gopalakrishnan. Training deep neural networks with 8-bit floating point numbers. In *NeurIPS*, 2018. 3
- [33] Oindrila Saha, Aditya Kusupati, Harsha Vardhan Simhadri, Manik Varma, and Prateek Jain. Rnnpool: Efficient non-linear pooling for ram constrained inference. *arXiv preprint arXiv:2002.11921*, 2020. 3
- [34] Peiye Liu, Bo Wu, Huadong Ma, Pavan Kumar Chundi, and Mingoo Seok. Memnet: Memory-efficiency guided neural architecture search with augment-trim learning. *arXiv preprint arXiv:1907.09569*, 2019. 3
- [35] 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. 3, 6
- [36] Ken Chatfield, Karen Simonyan, Andrea Vedaldi, and Andrew Zisserman. Return of the devil in the details: Delving deep into convolutional nets. In *BMVC*, 2014. 3, 7
- [37] Jeff Donahue, Yangqing Jia, Oriol Vinyals, Judy Hoffman, Ning Zhang, Eric Tzeng, and Trevor Darrell. Decaf: A deep convolutional activation feature for generic visual recognition. In *ICML*, 2014. 3, 7

- [38] Chuang Gan, Naiyan Wang, Yi Yang, Dit-Yan Yeung, and Alex G Hauptmann. Devnet: A deep event network for multimedia event detection and evidence recounting. In *CVPR*, pages 2568–2577, 2015. 3
- [39] Ali Sharif Razavian, Hossein Azizpour, Josephine Sullivan, and Stefan Carlsson. Cnn features off-the-shelf: an astounding baseline for recognition. In *CVPR Workshops*, 2014. 3, 7
- [40] Subhransu Maji, Esa Rahtu, Juho Kannala, Matthew Blaschko, and Andrea Vedaldi. Fine-grained visual classification of aircraft. *arXiv preprint arXiv:1306.5151*, 2013. 3, 6
- [41] Jonathan Krause, Michael Stark, Jia Deng, and Li Fei-Fei. 3d object representations for fine-grained categorization. In *Proceedings of the IEEE International Conference on Computer Vision Workshops*, 2013. 3, 6
- [42] Pramod Kaushik Mudrakarta, Mark Sandler, Andrey Zhmoginov, and Andrew Howard. K for the price of 1: Parameter efficient multi-task and transfer learning. In *ICLR*, 2019. 3, 7, 8
- [43] Simon Kornblith, Jonathon Shlens, and Quoc V Le. Do better imagenet models transfer better? In *CVPR*, 2019. 3, 6, 7, 8, 14
- [44] Yin Cui, Yang Song, Chen Sun, Andrew Howard, and Serge Belongie. Large scale fine-grained categorization and domain-specific transfer learning. In *CVPR*, 2018. 3, 6, 7, 8, 13
- [45] Pramod Kaushik Mudrakarta, Mark Sandler, Andrey Zhmoginov, and Andrew Howard. K for the price of 1: Parameter-efficient multi-task and transfer learning. In *ICLR*, 2019. 3, 6, 13
- [46] Jonathan Frankle, David J Schwab, and Ari S Morcos. Training batchnorm and only batchnorm: On the expressive power of random features in cnns. *arXiv preprint arXiv:2003.00152*, 2020. 3
- [47] Sergey Ioffe and Christian Szegedy. Batch normalization: Accelerating deep network training by reducing internal covariate shift. In *ICML*, 2015. 3, 4
- [48] Yuxin Wu and Kaiming He. Group normalization. In *ECCV*, 2018. 4
- [49] Prajit Ramachandran, Barret Zoph, and Quoc V Le. Searching for activation functions. In *ICLR Workshop*, 2018. 4
- [50] Bing Xu, Naiyan Wang, Tianqi Chen, and Mu Li. Empirical evaluation of rectified activations in convolutional network. *arXiv preprint arXiv:1505.00853*, 2015. 4
- [51] Maria-Elena Nilsback and Andrew Zisserman. Automated flower classification over a large number of classes. In *Sixth Indian Conference on Computer Vision, Graphics & Image Processing*, 2008. 6
- [52] Catherine Wah, Steve Branson, Peter Welinder, Pietro Perona, and Serge Belongie. The caltech-ucsd birds-200-2011 dataset. 2011. 6
- [53] Omkar M Parkhi, Andrea Vedaldi, Andrew Zisserman, and CV Jawahar. Cats and dogs. In *CVPR*, 2012. 6
- [54] Lukas Bossard, Matthieu Guillaumin, and Luc Van Gool. Food-101—mining discriminative components with random forests. In *ECCV*, 2014. 6
- [55] Alex Krizhevsky and Geoffrey Hinton. Learning multiple layers of features from tiny images. Technical report, Citeseer, 2009. 6
- [56] Ziwei Liu, Ping Luo, Xiaogang Wang, and Xiaoou Tang. Large-scale celebfaces attributes (celeba) dataset. Retrieved August, 2018. 6
- [57] Qiong Cao, Li Shen, Weidi Xie, Omkar M Parkhi, and Andrew Zisserman. Vggface2: A dataset for recognising faces across pose and age. In *2018 13th IEEE International Conference on Automatic Face & Gesture Recognition (FG 2018)*, 2018. 6
- [58] Alexander Kolesnikov, Lucas Beyer, Xiaohua Zhai, Joan Puigcerver, Jessica Yung, Sylvain Gelly, and Neil Houlsby. Big transfer (bit): General visual representation learning. *arXiv preprint arXiv:1912.11370*, 2019. 6
- [59] Siyuan Qiao, Huiyu Wang, Chenxi Liu, Wei Shen, and Alan Yuille. Weight standardization. *arXiv preprint arXiv:1903.10520*, 2019. 6
- [60] Diederik P Kingma and Jimmy Ba. Adam: A method for stochastic optimization. *arXiv preprint arXiv:1412.6980*, 2014. 6

- [61] Ilya Loshchilov and Frank Hutter. Sgdr: Stochastic gradient descent with warm restarts. *arXiv preprint arXiv:1608.03983*, 2016. 6
- [62] Kaiming He, Xiangyu Zhang, Shaoqing Ren, and Jian Sun. Deep residual learning for image recognition. In *CVPR*, 2016. 8
- [63] Zichao Guo, Xiangyu Zhang, Haoyuan Mu, Wen Heng, Zechun Liu, Yichen Wei, and Jian Sun. Single path one-shot neural architecture search with uniform sampling. *arXiv preprint arXiv:1904.00420*, 2019. 13

A Details of Feature Extractor Adaptation

Conventional transfer learning chooses the feature extractor according to the pre-training accuracy (e.g., ImageNet accuracy) and uses the same one for all transfer tasks [44, 45]. However, we find this approach sub-optimal since different target tasks may need very different feature extractors, and high pre-training accuracy does not guarantee good transferability of the pre-trained weights. This is especially critical in our case where the weights are frozen.

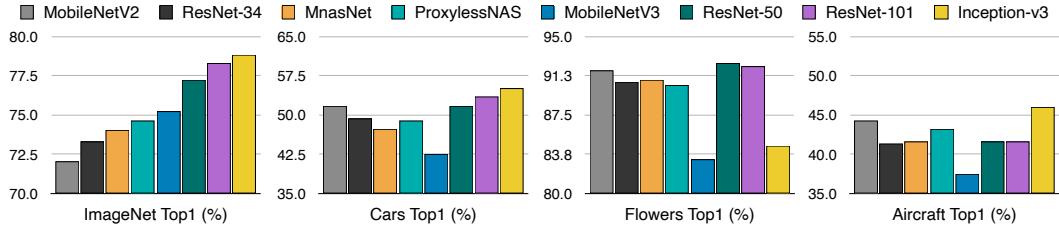


Figure 6: Transfer learning performances of various ImageNet pre-trained models with the last linear layer trained. The relative accuracy order between different pre-trained models changes significantly among ImageNet and the transfer learning datasets.

Figure 6 shows the top1 accuracy of various widely used ImageNet pre-trained models on three transfer datasets by only learning the last layer, which reflects the transferability of their pre-trained weights. The relative order between different pre-trained models is not consistent with their ImageNet accuracy on all three datasets. This result indicates that the ImageNet accuracy is not a good proxy for transferability. Besides, we also find that the same pre-trained model can have very different rankings on different tasks. For instance, Inception-V3 gives poor accuracy on Flowers but provides top results on the other two datasets.

Therefore, we need to specialize the feature extractor to best match the target dataset. In this work, we achieve this by using a pre-trained once-for-all network [10] that comprises many different sub-networks. Specifically, given a pre-trained once-for-all network on ImageNet, we fine-tune it on the target transfer dataset with the weights of the main branches (i.e., MB-blocks) frozen and the other parameters (i.e., biases, lite residual modules, classifier head) updated via gradient descent. In this phase, we randomly sample one sub-network in each training step. The peak memory cost of this phase is 61MB under resolution 224, which is reached when the largest sub-network is sampled. Regarding the computation cost, the average MAC (forward & backward)⁴ of sampled sub-nets is $(776\text{M} + 2510\text{M}) / 2 = 1643\text{M}$ per sample, where 776M is the training MAC of the smallest sub-network and 2510M is the training MAC of the largest sub-network. Therefore, the total MAC of this phase is $1643\text{M} \times 2040 \times 0.8 \times 50 = 134\text{T}$ on Flowers, where 2040 is the number of total training samples, 0.8 means the once-for-all network is fine-tuned on 80% of the training samples (the remaining 20% is reserved for search), and 50 is the number of training epochs.

Based on the fine-tuned once-for-all network, we collect 500 [sub-net, accuracy] pairs on the validation set (20% randomly sampled training data) and train an accuracy predictor⁵ using the collected data [10]. We employ evolutionary search [63] based on the accuracy predictor to find the sub-network that best matches the target transfer dataset. No back-propagation on the once-for-all

⁴The training MAC of a sampled sub-network is roughly 2× larger than its inference MAC, rather than 3×, since we do not need to update the weights of the main branches.

⁵Details of the accuracy predictor is provided in Appendix B.

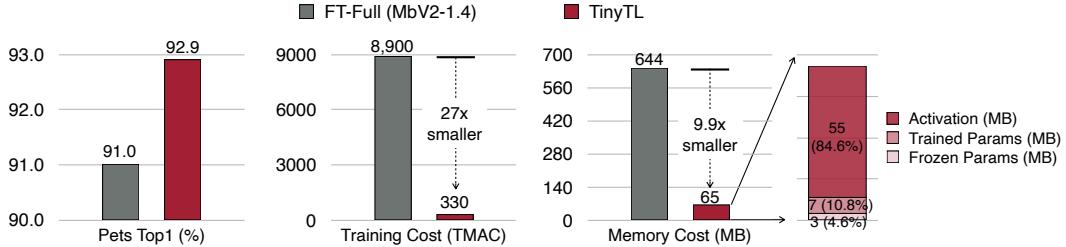


Figure 7: On-device training cost on Pets. TinyTL requires $9.9\times$ smaller memory cost (assuming using the same batch size) and $27\times$ smaller computation cost compared to fine-tuning the full MobileNetV2-1.4 [43] while having a better accuracy.

network is required in this step, thus incurs no additional memory overhead. The primary computation cost of this phase comes from collecting 500 [sub-net, accuracy] pairs required to train the accuracy predictor. It only involves the forward processes of sampled sub-nets, and no back-propagation is required. The average MAC (only forward) of sampled sub-nets is $(355M + 1182M) / 2 = 768.5M$ per sample, where 355M is the inference MAC of the smallest sub-network and 1182M is the inference MAC of the largest sub-network. Therefore, the total MAC of this phase is $768.5M \times 2040 \times 0.2 \times 500 = 157T$ on Flowers, where 2040 is the number of total training samples, 0.2 means the validation set consists of 20% of the training samples, and 500 is the number of measured sub-nets.

Finally, we fine-tune the searched sub-network with the weights of the main branches frozen and the other parameters updated, using the full training set to get the final results. The memory cost of this phase is 66MB under resolution 256 on Flowers. The total MAC is $2190M \times 2040 \times 1.0 \times 50 = 223T$, on Flowers, where 2190M is the training MAC, 2040 is the number of total training samples, 1.0 means the full training set is used, and 50 is the number of training epochs.

B Details of the Accuracy Predictor

The accuracy predictor is a three-layer feed-forward neural network with a hidden dimension of 400 and ReLU as the activation function for each layer. It takes the one-hot encoding of the sub-network’s architecture as the input and outputs the predicted accuracy of the given sub-network. The inference MAC of this accuracy predictor is only 0.37M, which is 3-4 orders of magnitude smaller than the inference MAC of the CNN classification models. The memory footprint of this accuracy predictor is only 5KB. Therefore, both the computation overhead and the memory overhead of the accuracy predictor are negligible.

C Cost Details

The on-device training cost of TinyTL and *FT-Full* on Pets is summarized in Figure 7 (left side), while the memory cost breakdown of TinyTL is provided in Figure 7 (right side). Compared to fine-tuning the full MobileNetV2-1.4, TinyTL not only greatly reduces the activation size but also reduces the parameter size (by applying weight quantization on the frozen parameters) and the training cost (by not updating weights of the feature extractor and using fewer training steps). Specifically, TinyTL reduces the memory footprint by $9.9\times$, and reduces the training computation by $27\times$ without loss of accuracy. Therefore, TinyTL is not only more memory-efficient but also more computation-efficient.