LITE TRANSFORMER WITH LONG-SHORT RANGE ATTENTION

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ABSTRACT

Transformer has become ubiquitous in natural language processing (*e.g.*, machine translation, question answering); however, it requires enormous amount of computations to achieve high performance, which makes it not suitable for mobile applications since mobile phones are tightly constrained by the hardware resources and battery. In this paper, we investigate the mobile setting (under 500M Mult-Adds) for NLP tasks to facilitate the deployment on the edge devices. We present *Long-Short Range Attention* (LSRA), where one group of heads specializes in the local context modeling (by convolution) while another group captures the long-distance relationship (by attention). Based on this primitive, we design *Lite Transformer* that is tailored for the mobile NLP application. Our Lite Transformer demonstrates consistent improvement over the transformer on three well-established language tasks: machine translation, abstractive summarization, and language modeling. It outperforms the transformer on WMT'14 English-French by 1.2 BLEU under 500M Mult-Adds and 1.7 BLEU under 100M Mult-Adds, and reduces the computation of transformer base model by 2.5×. Further, with general techniques, our Lite Transformer achieves **18.2**× model size compression. For language modeling, our Lite Transformer also achieves 3.8 lower perplexity than the transformer around 500M Mult-Adds. Without the costly architecture search that requires more than 250 GPU **years**, our Lite Transformer outperforms the AutoML-based Evolved Transformer by 0.5 higher BLEU under the mobile setting.

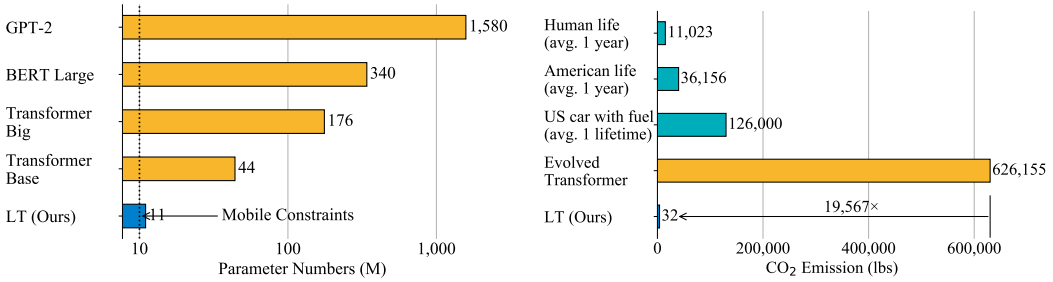
1 INTRODUCTION

Transformer (Vaswani et al., 2017) has prevailed among various areas of natural language processing due to its high training efficiency and superior capability in capturing long-distance dependencies. Building on top of them, modern state-of-the-art models, such as BERT (Devlin et al., 2019), are able to learn powerful language representations from unlabeled text and even surpass the human performance on the challenging question answering task.

However, the good performance come at high computational cost. For example, a single transformer deep model executes more than 10G Mult-Adds in order to translate a sentence of only 30 words. Such extremely high computational resources requirement is beyond the capabilities of many edge devices such as smartphones and IoTs. Therefore, it is of great importance to design efficient and fast transformer architecture specialized for real-time NLP applications on the edge. Automatic neural architecture search (Zoph & Le, 2017; So et al., 2019) is a choice for high accuracy model design, but the massive searching cost raises much concern (Figure 1b).

In this paper, we mainly focus on the efficient inference scenario for mobile devices, where the total number of Mult-Adds is constrained to be lower than 500M. A straightforward way to reduce the computation of the transformer is to shrink the embedding size directly. Although it can effectively reduce both model size and computation, it also weakens the model capacity capturing the long and short distance relationship at the same time. To this end, we systematically studied the computation breakdown of the transformer and observed that the computation is dominated by the feed-forward network (FFN), not the attention. We discovered that the prevailing bottleneck-structured transformer block is not efficient. We then present a novel Long-Short Range Attention (LSRA) primitive. LSRA

∗ indicates equal contributions.



(a) Parameter numbers of modern NLP models. (b) The design cost measured in CO_2 emission (lbs).

Figure 1: Left: the size of recent NLP models grows rapidly and exceeds the mobile constraints by a large extend. Right: the search cost of AutoML-based NLP models is considerable, which emits carbon dioxide nearly five times the lifetime emissions of the average car.

trades off the computation in FFN for wider attention layers. It stretches the bottleneck to introduce more dependency capturing capability for the attention layer, and then shrink the embedding size to reduce the total computation amount while maintaining the same performance. Instead of having one module for "general" information, LSRA dedicates *specialized* heads to model long and short distance contexts. Inspired by Wu et al. (2019b), LSRA introduces convolution in a parallel branch to extract local dependencies so that the attention branch can focus on long-distance context modeling. By stacking this primitive, we build Lite Transformer (LT) for mobile NLP applications.

Extensive experiments demonstrate that our Lite Transformer model offers significant improvements over the transformer on three lanugage tasks: machine translation, abstractive summarization and language modeling. For machine translation, on IWSLT 2014 German-English, it outperforms the transformer by 2.1 BLEU under 100M Mult-Adds; on WMT 2014 English-German, it surpasses the transformer by 0.4 BLEU under 500M Mult-Adds and 1.2 BLEU under 100M Mult-Adds; on WMT 2014 English-French, it also achieves consistent improvements over the transformer: 1.2 BLEU under 500M Mult-Adds and 1.7 BLEU under 100M Mult-Adds. For summarization, on CNN-DailyMail, it reduces the computation of the transformer base model by 2.4×. For the language modeling, it achieves 3.8 lower perplexity than the transformer around 500M Mult-Adds.

Guided by our design insights, our manually-designed Lite Transformer also achieves 0.5 higher BLEU than the AutoML-based Evolved Transformer (So et al., 2019), which requires more than 250 GPU years to search, emitting as much carbon as five cars in their lifetimes (see Figure 1b). It indicates that AutoML is not a panacea: careful analysis and design insights (*i.e.*, removing bottleneck, specialized heads) can effectively prune the search space and improve the sample efficiency.

The contribution of this paper has four aspects:

1. We systematically analyze the commonly used computation bottleneck structure in modern neural networks and argue that the bottleneck design is not optimal for 1-D attention.

2. We propose a specialized multi-branch feature extractor, Long-Short Range Attention (LSRA), as the basic building block of our transformer, where convolution helps capture the local context and attention concentrates on global context feature.

3. We build Lite Transformer based on our LSRA. Under mobile computation resource constraints (500M Mult-Adds), our Lite Transformer demonstrates coherent improvement on three widely used machine translation datasets. With extra experiments, Lite Transformer is efficient on multiple language applications.

4. Even compared to AutoML-searched Evolved Transformer, our Lite Transformer offers 0.5 more BLEU score on WMT En-De dataset, saving the design cost by 20000× in CO_2 emissions. It alerts us to rethink the practicality of AutoML in terms of design cost.

2 Related Work

RNNs and CNNs. Recurrent neural networks (RNNs) have prevailed various sequence modeling tasks for a long time (Sutskever et al., 2014; Luong et al., 2015; Bahdanau et al., 2015; Wu et al., 2016). However, RNNs cannot be run parallelly across the sequence due to its temporal dependency. Recently, some work has demonstrated that RNN is not an essential component to achieve the state-of-the-art performance. For instance, researchers have proposed highly-efficient convolution-based models (Kalchbrenner et al., 2016; Gehring et al., 2017; Kaiser et al., 2018; Wu et al., 2019b). Convolution is an ideal primitive to model the local context information; however, it lacks the ability to capture the long-distance relationship, which is critical in many sequence modeling tasks.

Transformers. As an alternative, attention is able to capture global-context information by pairwise correlation. Transformer (Vaswani et al., 2017) has demonstrated that it is possible to stack the self-attentions to achieve the state-of-the-art performance. Recently, there have been a lot of variants to the transformer (Ahmed et al., 2017; Ott et al., 2018; Chen et al., 2018; Paulus et al., 2018; Shaw et al., 2018; Sukhbaatar et al., 2019a;b; Child et al., 2019). Among them, Ott et al. (2018) proposed to scale up the batch size; Shaw et al. (2018) leverages the relative position representations; Ahmed et al. (2017) introduces the weighted multi-head attention; Sukhbaatar et al. (2019a) applies adaptive masks for long-range information on character-level language modeling with very long sequences. All these attempts are orthogonal to our work, as we focus on improving the neural network architecture itself, and not the general techniques used for improving overall performance.

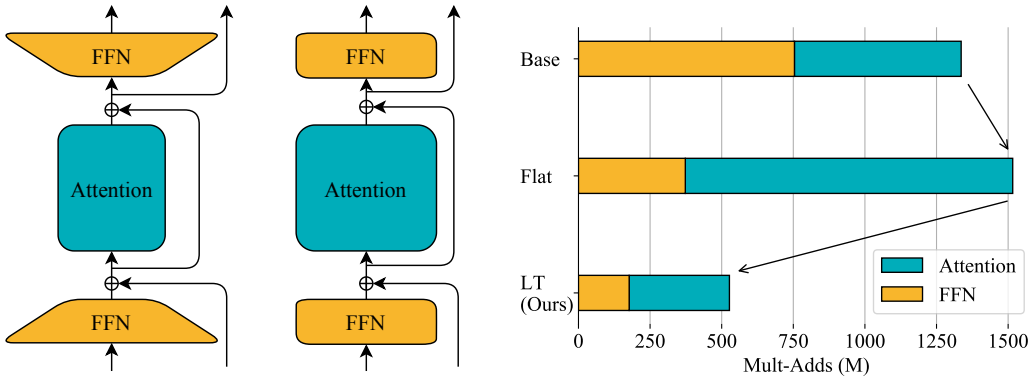
Automated Model Design. Due to the vast architecture design space, there has been an increasing trend of automating the compact model design using the neural architecture search (NAS) (Zoph & Le, 2017; Zoph et al., 2018; Pham et al., 2018; Cai et al., 2019a) and integrating the hardware resource constraints into the optimization loop, such as MnasNet (Tan et al., 2018), ProxylessNAS (Cai et al., 2019b) and FBNet (Wu et al., 2019a). In the NLP community, the evolved transformer (So et al., 2019) adopts the neural architecture search (Zoph & Le, 2017) for basic blocks and finds a better #parameter-BLEU trade-off for the transformer. However, all these AutoML-based model design requires significant amount of GPU hours to find the 'best' model, which is not affordable for most researchers.

Model Acceleration. Apart from designing efficient models directly, another approach to achieve the efficient inference is to compress and accelerate the existing large models. For instance, some have proposed to prune the separate neurons (Han et al., 2015b; 2016) or the entire channels (He et al., 2017; Liu et al., 2017; He et al., 2018); others have proposed to quantize the network (Courbariaux et al., 2016; Zhu et al., 2017; Krishnamoorthi, 2018; Wang et al., 2019) to accelerate the model inference. Recently, AutoML has also been used to automate the model compression and acceleration (Yang et al., 2018; He et al., 2018; Wang et al., 2019; Liu et al., 2019). All these techniques are effective for arbitrary models and are therefore orthogonal to our approach, while we aim to explore how to make use to the domain knowledge of natural language processing.

3 Is Bottleneck Effective for 1-D Attention?

Attention mechanism has been widely used in various applications, including 1-D (language processing (Vaswani et al., 2017)), 2-D (image recognition) and 3-D (video recognition (Wang et al., 2018)). It computes pairwise dot-product between all the input elements to model both short-term and long-term relationships. Despite its effectiveness, the operation introduces massive computation. Assume the number of elements (*e.g.*, length of tokens in language processing, number of pixels in image, *etc.*) fed to attention layer is N, and the dimension of features (*i.e.*, channels) is d, the computation needed for the dot-product is N^2d. For images and videos, N is usually very large. For example, the intermediate feature map in a video network (Wang et al., 2018) has 16 frames, each with 112×112 resolution, leading to $N = 2 \times 10^5$. The computation of convolution and fully-connected layers grows linearly w.r.t. N, while the computation of attention layers grows quadratically w.r.t. N. The computation of attention module will soon overwhelm with a large N.

To address the dilemma, a common practice is to first reduce the number of channels d using a linear projection layer before applying attention, and increase the dimension afterwards (as shown in Figure 2a). In the original design of transformer (Vaswani et al., 2017), the channel dimension



(a) Vanilla and flattened transformer block.

(b) Mult-Adds breakdown for attention and FFN.

Figure 2: Flattening the bottleneck of transformer blocks increases the proportion of the attention versus the FFN, which is good for further optimization for attention.

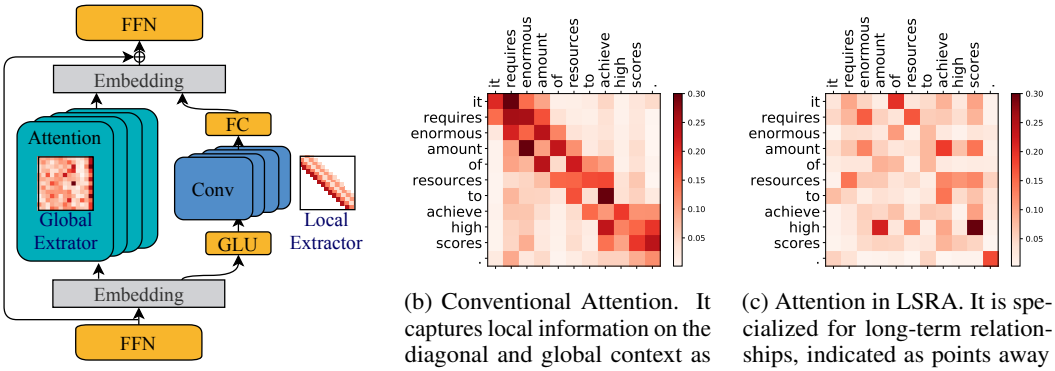
	Embedding	#Mult-Adds	Attention	BLEU (on WMT En-Fr)
Vaswani et al. (2017)	512-2048	1.3G	44%	38.1
So et al. (2019)	512-2048	1.3G	44%	40.0
Our Reimplementation	512-2048	1.3G	44%	39.9
Transformer (*Flattened*)	720-720	1.5G	**75%**	**41.0**
Lite Transformer (w. LSRA)	496-496	**527M**	66%	**39.6**

Table 1: Bottleneck design is not optimal for 1-D attention. The 'flattened' version of Transformer does not harm the BLEU score, but makes the attention take the major computation for further optimization.

in the attention module is 4 times smaller than that in the FFN layer. Similarly, in non-local video network (Wang et al., 2018), the channel number is first reduced by half before applying non-local attention module. This practice saves the computation by 16 or 4 times. Nevertheless, it also *decreases* the feature modeling ability of attention layers with a smaller feature dimension. The situation could be even worse for language processing, as attention is the major module for feature modeling (unlike images and videos where convolutions conduct the major modeling).

For tasks like translation, the length of the input sequence N tends to be small, which is around 20-30 in common cases. A transformer block consists of an attention (or two for decoder), followed by a feed-forward network (FFN). For the attention layer, the Mult-Adds would be $\mathcal{O}(4Nd^2 + N^2d)$; for FFN, the Mult-Adds is $\mathcal{O}(2 \times 4Nd^2)$. Given a small N, it is doubtful if the bottleneck design is a good trade-off between computation and accuracy on 1D attention. To verify the idea, we first profile the computation makeup in the transformer in Figure 2b. Surprisingly, for the original transformer (denoted as 'base' in the figure), FFN layer actually consumes much of the computation. This is not desirable since FFN itself cannot perform any context modeling. In conclusion, due to the small N, bottleneck design cannot significantly reduce the computation in 1D attention, while the limited benefit is further compromised by the FFN layer; it also harms the capacity of attention layer due to smaller dimension, which is the major context modeling unit in the transformer.

Therefore, we argue that the bottleneck design is not optimal for 1-D attention. We instead design a 'flattened' version of transform block that does not reduce and increase the channel dimension. With the new design, the attention part now takes up the major computation in the flat transformer model ('Flat' in Figure 2b), leaving a larger space for further optimization. We also test the performance change of such modification on IWSLT and WMT datasets (Table 1). On IWSLT De-En task, our Flatten Transformer can achieve similar BLEU score using less than half computation compared to the original transformer; on WMT, we can achieve comparable performance at a slightly larger computation, which can be easily reduced with further optimization on the attention heads.



(a) Lite Transformer block

(b) Conventional Attention. It captures local information on the diagonal and global context as sparse points. (Redundant)

(c) Attention in LSRA. It is specialized for long-term relationships, indicated as points away from the diagonal. (Efficient)

Figure 3: Model architecture (a) and the visualization of attention weights. Conventional attention (b) put too much emphasizes on local relationship modeling (see the diagonal structure). We specialize the local feature extraction by a convolutional branch which efficiently models locality, so that the attention branch can specialize on global feature extraction (c).

4 Long-Short Range Attention (LSRA)

Since the attention-based network made a great progress in NLP, researchers have tried to understand what the exact information an attention captures. Kovaleva et al. (2019) and Clark et al. (2020) visualized the attention weights from different layers in BERT. As shown in Figure 3b, the weight w illustrate the relationships between the words from the source sentence and the target sentence (the same for self-attention). With a greater weight w_{ij} (darker color), the i-th word in the source has more attention focus on the j-th word in the target. And the focus of an attention module typically has some strong patterns: sparse points, vertical lines and diagonal groups. The three of them respectively represent the relationships between some particular words, the long term information and the correlation in small neighborhoods. We denotes the former two as "global" relationships and the last one as "local".

In order to provide both the global and local information for a translation task, the attention modules have to extract all of those features with exactly the same architecture, requiring a large capacity. That is not an optimal case since, taking hardware design as an example, devices for general purpose, like CPUs, tend to be more redundant than specialized ones, like FPGAs. When the model capacity is relatively large, the redundancy can be tolerated and may even provides a better performance. However, when it comes to mobile applications, a model should be more efficient due to the computation and power constraints. To tackle the problem, instead of having one module for "general" information, we propose a more specialized architecture, *Long-Short Range Attention (LSRA)*, that captures the global and local information separately.

As shown in Figure 3a, our LSRA module follows a two-branch design. The left branch captures global context, while the right branch models local information. Instead of feeding the whole input to both branch, we split it into two parts along the channel dimension, which will be mixed by the following FFN layer. Such a practice reduces the overall computation by 2 times. The left branch is a normal attention model as in Vaswani et al. (2017), while the channel dimension is reduced by half. For the right branch of local relationships, one natural idea is to apply convolution over sequence. With a sliding window, the diagonal groups can be easily covered by the module. To further reduce the computation, we replace the normal convolution with a lighter version (Wu et al., 2019b) consisting of linear layers and depth-wise convolution. In this manner, we place the attention and the convolutional module side by side, encouraging them to have different perspective of the sentence, globally and locally, so that the architecture can then benefit from the specialization and achieve a better efficiency.

To have a better insight, we visualized the average attention weights of the same layer for a fully trained basic Transformer and our Lite Transformer in Figure 3. It can be easily distinguished that instead of attempting to model both global and local features, the attention module in LSRA only focus on the global, leaving the local context modeling to the convolution branch.

5 EXPERIMENTAL SETUP

5.1 MOBILE SETTINGS

Most of machine translation architectures benefit from the large model size and computational complexity. However, edge devices, such as mobile phones and IoTs, is highly computationally limited. Those massive architectures are no more suitable for real-world mobile applications.

- The floating-point performance of the ARM Cortex-A72 mobile CPU is about 48G FLOPS (4 cores @1.5GHz). To achieve the peak performance of 50 sentences per second, the model should be less than 960M FLOPs (480M Mult-Adds). That is a common constraint in the computer vision community. For example, Liu et al. (2018) also uses 500M Mult-Adds as the constraint of its mobile setting. Therefore, we define the mobile settings for machine translation tasks: the computation constraint should be under **500M Mult-Adds** (or 1G FLOPs) with a sequence of 30 tokens (general length for machine translation).
- Additionally, we set a limitation for the parameters of the models. The constraint is based on the download limitation. When an application is larger than 100MB, it cannot be downloaded with 4G LTE (only with WIFI) in the App Store. Therefore, the number of parameters for a mobile model should be limited. As MobileNet contains around 7M parameters, we round it to the nearest magnitude, 10M parameters, as our constraint.

5.2 DATASETS AND EVALUATION

Machine Translation. The results are based on three machine translation benchmarks: For IWSLT'14 German-English (De-En), we follow the settings in Grave et al. (2017) with 160K training sentence pairs and 10K joint byte pair encoding (BPE) (Sennrich et al., 2016) vocabulary in lower case. For WMT English to German (En-De), we train the model on WMT'16 training data with 4.5M sentence pairs, validate on newstest2013, and test on newstest2014, the same as Wu et al. (2019b). Moreover, the vocabulary used a 32K joint source and target BPE. For WMT English to Franch (En-Fr), we replicate the setup in Gehring et al. (2017) with 36M training sentence pairs from WMT'14, validate on newstest2012 and 2013, and test on newstest2014. Also, the 40K vocabulary is based on a joint source and target BPE factorization.

For evaluation, we use the same beam decoding configuration used by Vaswani et al. (2017), where there is a beam size of 4 and a length penalty of 0.6. All BLEUs are calculated with case-sensitive tokenization[*], but for WMT En-De, we also use the compound splitting BLEU[†], the same as Vaswani et al. (2017). When testing, we average the last 10 model checkpoints for IWSLT De-En and take the model with the lowest perplexity on the validation set for the WMT datasets. We omit the word embedding lookup table from the model parameters since the number of entries in the table would highly differ for various tasks using transformer. For the Mult-Adds, we calculate the total number of multiplication-addition pairs for a model translating a sequence with the length of 30 to a sequence with the same length, which is the average length for sentence-level machine translation tasks.

Abstractive Summarization. We also evaluate our LT on CNN-DailyMail dataset (Hermann et al., 2015) for abstractive summarization. The dataset contains 280K news articles paired with multi-sentence summaries. We truncate the articles to 1000 tokens and use a 30K BPE vocabulary. We use F1-Rouge as the metric, including Rouge-1 (R-1), Rouge-2 (R-2) and Rouge-L (R-L) (Lin, 2004)[‡]. We follow the generation settings in Lewis et al. (2019). We omit the word embedding lookup table and softmax layer from both the model parameters and #Mult-Adds calculation. #Mult-Adds is calculated for the documents with the input length of 30, 100, and 1000 and the output length of 60 (the average tokens for the output of CNN-DailyMail dataset).

Language Modeling. We test our LT for language modeling task on WIKITEXT-103, which comprises about 100M tokens and a 260K BPE vocabulary. We evaulate the perplexity on both the validation set and the training set. The model parameters and #Mult-Adds are also computed for the input with a length of 30, 100m and 1000.

[*] https://github.com/moses-smt/mosesdecoder/blob/master/scripts/generic/multi-bleu.perl

[†] https://github.com/tensorflow/tensor2tensor/blob/master/tensor2tensor/utils/get_ende_bleu.sh

[‡] https://github.com/pltrdy/files2rouge

	#Parameters	#Mult-Adds	BLEU	ΔBLEU
Transformer (Vaswani et al., 2017)	2.8M	63M	27.8	–
LightConv (Wu et al., 2019b)	2.5M	52M	28.5	+0.7
Lite Transformer (Ours)	2.8M	54M	**30.9**	**+3.1**
Transformer (Vaswani et al., 2017)	5.7M	139M	31.3	–
LightConv (Wu et al., 2019b)	5.1M	115M	31.6	+0.3
Lite Transformer (Ours)	5.4M	119M	**32.9**	**+1.6**
Transformer (Vaswani et al., 2017)	8.5M	215M	32.7	–
LightConv (Wu et al., 2019b)	8.4M	204M	32.9	+0.2
Lite Transformer (Ours)	8.9M	209M	**33.6**	**+0.9**

Table 2: Results on IWSLT'14 De-En. Our Lite Transformer outperforms the transformer (Vaswani et al., 2017) and the Lightweight convolution network (Wu et al., 2019b) especially in mobile settings.

			WMT'14 En-De		WMT'14 En-Fr	
	#Parameters	#Mult-Adds	BLEU	ΔBLEU	BLEU	ΔBLEU
Transformer (Vaswani et al., 2017)	2.8M	87M	21.3	–	33.6	–
Lite Transformer (Ours)	2.9M	90M	**22.5**	**+1.2**	**35.3**	**+1.7**
Transformer (Vaswani et al., 2017)	11.1M	338M	25.1	–	37.6	–
Lite Transformer (Ours)	11.7M	360M	**25.6**	**+0.5**	**39.1**	**+1.5**
Transformer (Vaswani et al., 2017)	17.3M	527M	26.1	–	38.4	–
Lite Transformer (Ours)	17.3M	527M	**26.5**	**+0.4**	**39.6**	**+1.2**

Table 3: Results on WMT'14 En-De and WMT'14 En-Fr. Our Lite Transformer improves the BLEU score over the transformer under similar Mult-Adds constraints.

5.3 ARCHITECTURE

The model architecture is based on the sequence to sequence learning encoder-decoder (Sutskever et al., 2014). For machine translation, our baseline model is based on the one proposed by Vaswani et al. (2017) for WMT. For IWSLT, we follow the settings in Wu et al. (2019b). We also adopt the same model as on WMT for summarization task. For language modeling, our model is in line with Baevski & Auli (2019) but with smaller model dimension $d_{\text{model}} = 512$ and layer number $L = 12$ for the resource constraint. We use fairseq's re-implementation (Ott et al., 2019) of transformer base model as the backbone.

In our architecture, we first flatten the bottleneck from the transformer base model and then replace the self-attention with the LSRA. More specifically, we use two specialized modules, an attention branch and a convolutional branch. Both the input and the output of the convolution are transformed by fully connected layers (GLU is applied for the input on WMT), and the kernel is dynamically calculated from the input using a fully connected layer in the WMT models. The kernel sizes are [3, 5, 7, 31×3] for both the encoder and the decoder (Wu et al., 2019b), and the number of heads for each module is 4 (half of the heads number in the transformer base model). The model for summarization is the same as the WMT model. For language modeling, the kernel sizes for the convolution branch are [15, 15, 31×4, 63×6].

5.4 TRAINING SETTINGS

All of our training settings for machine translation are in line with Wu et al. (2019b). We use a dropout of 0.3 for both the WMT and IWSLT datasets and linearly scale down the dropout ratio when shrinking the dimension of the embeddings for the WMT datasets. Same as Wu et al. (2019b), we apply Adam optimizer and a cosine learning rate schedule (Kingma & Ba, 2015; Loshchilov & Hutter, 2017) for the WMT models, where the learning rate is first linearly warm up from 10^{-7} to 10^{-3} followed by a cosine annealing with a single cycle. For IWSLT De-En, we use inverse square root learning rate scheduling (Vaswani et al., 2017) with the linear warm-up. We use the same

	#Params	#Mult-Adds	BLEU	GPU Hours	CO_2e (lbs)	Cloud Computation Cost
Transformer (Vaswani et al., 2017)	2.8M	87M	21.3	8×12	26	$68 - $227
Evolved Transformer (So et al., 2019)	3.0M	94M	22.0	8×274K	626K	$1.6M - $5.5M
Lite Transformer (Ours)	2.9M	90M	**22.5**	8×14	32	$83 - $278
Transformer (Vaswani et al., 2017)	11.1M	338M	25.1	8×16	36	$93.9 - $315
Evolved Transformer (So et al., 2019)	11.8M	364M	25.4	8×274K	626K	$1.6M - $5.5M
Lite Transformer (Ours)	11.7M	360M	**25.6**	8×19	43	$112 - $376

Table 4: Performance and training cost of an NMT model in terms of CO_2 emissions (lbs) and cloud compute cost (USD). The training cost estimation is adapted from Strubell et al. (2019). The training time for transformer and our Lite Transformer is measured on NVIDIA V100 GPU. The cloud computation price is based on the AWS.

training settings for summarization. For the language modeling task, the training settings are in line with Baevski & Auli (2019). We decrease the dropout ratio for the FFN layer by half in our LT due to the flattened layer.

We train WMT and summarization models on 16 NVIDIA RTX 2080Ti GPUs and IWSLT De-En on a single GPU for 50K steps. We also accumulate the gradients for 8 batches before each model update (Ott et al., 2018). The gradients of IWSLT models are not accumulated. The maximum number of tokens in a batch is 4K for all the models. Label smooth of 0.1 is applied for the prior distribution over the vocabulary (Szegedy et al., 2016; Pereyra et al., 2017). For language modeling, we train the models on 24 GPUs for 286K steps, the same as the settings in Baevski & Auli (2019).

6 Results

6.1 Machine Translation

Results on IWSLT. We first report the result on IWSLT'14 De-En dataset. The baseline model is the same as the one used in Wu et al. (2019b), which provides the best results in the literature with 512 embedding dimension, 1024 FFN hidden dimension, and 4 heads for all the attentions. Our Lite Transformer generally outperforms the base transformer on mobile constraints. With tighter computation limitations, our model achieves more significant improvement. That is because, when the dimension of the embedding decreases, it becomes much harder for the "general" attention to extract both the global and local features from the rather more compact information within the embedding. On the contrary, with the specialized LSRA, our model can capture the information from the embedding more effectively.

In Table 2, we present the quantitative results of our Lite Transformer on IWSLT'14 De-En dataset, comparing to the transformer baseline as well as the LightConv (Wu et al., 2019b). Around 100M Mult-Adds, our model even achieves 1.6 BLEU score improvement than the transformer.

Results on WMT. We also show the result on the WMT'14 En-De and WMT'14 En-Fr dataset. Similar to the IWSLT, our Lite Transformer achieves a better trade-off with regard to transformer (Vaswani et al., 2017) against the total computation and the number of model parameters on mobile settings. The quantitative results in Table 3 indicates that our specialized LT has 1.2 and 1.7 BLEU score improvement under 100M Mult-Adds and 0.5 and 1.5 around 300M Mult-Adds for WMT En-De dataset and WMT En-Fr dataset respectively.

6.2 Comparison with Automated Design

Comparing with the AutoML-based Evolved Transformer (ET) (So et al., 2019), our Lite Transformer also shows a significant improvement in mobile settings. Moreover, within mobile settings, the LT outperforms the ET by 0.5 and 0.4 BLEU scores under 100M and 300M Mult-Adds, respectively, as shown in Table 4. Our architecture design is different from ET's design: ET stacks attentions and convolutions sequentially, while our LT puts them in parallel; also, ET does not flatten the FFN.

	#Params	#MAdds (30)	#MAdds (100)	#MAdds (1000)	R-1	R-2	R-L
Transformer	44.1M	2.0G	3.6G	29.9G	41.4	18.9	38.3
LT (Ours)	**17.3M**	**0.8G**	**1.5G**	**12.5G**	41.3	18.8	38.3

Table 5: Quantitative results on CNN-DailyMail dataset for abstractive summarization task. Our LT achieves similar F1-Rouge (R-1, R-2 and R-L) to the transformer (Vaswani et al., 2017) with more than 2.4× less computation and 2.5× less model size. "#MAdds (x)" indicates the #Mult-Adds required by the model with the input length of x.

	#Params	#MAdds (30)	#MAdds (100)	#MAdds (1000)	Valid ppl.	Test ppl.
ADP	18.9M	578M	2.0G	31.2G	26.8	27.5
LT (Ours)	19.2M	580M	2.0G	26.8G	**22.9**	**23.7**

Table 6: Quantitative results on WIKITEXT-103 dataset for language modeling task. We apply our LT architecture on transformer base model with adaptive inputs (ADP) (Baevski & Auli, 2019) and achieve 3.8 lower test perplexity under similar resource constraint.

	Model Size	Compression Ratio	BLEU
Transformer	176MB	–	39.9
Lite Transformer	69.2MB	2.5×	39.6
Lite Transformer + Quantization (8-bit)	17.3MB	10.2×	39.6
Lite Transformer + Pruning + Quantization (8-bit)	9.7MB	**18.2**×	39.5

Table 7: Our Lite Transformer with general compression techniques on WMT En-Fr dataset.

Though nowadays, neural architecture search has been proved to be very powerful for searching in a large design space, the huge cost, more than 626155 lbs CO_2 emissions and more than 250 GPU years, cannot be ignored. Instead, careful human design with intuitions for specific tasks can also be a great choice in practice to save a large number of resources for the earth.

6.3 Abstractive Summarization and Language Modeling

We also test our Lite Transformer on longer input. In Table 5, we report results on CNN-DailyMail dataset for abstractive summarization. Our model achieves a similar F1-Rouge score as the transformer base model but requires 2.4× less computation and 2.5× storage resources. In Table 6, we provides the results of our Lite Transformer on WIKITTEXT-103 for language modeling task, compared with the adaptive inputs Baevski & Auli (2019) baseline. Under similar resource constraints, our LT can achieve 3.9 and 3.8 lower perplexity on valid and test set, respectively. Despite the machine translation tasks, the specialization design in LSRA is effective for larger scale sequence-to-sequence modeling tasks. Thanks to the convolution branch for local information, attention branches in LSRA can extract global information from the long context. These extensive experiments indicate that our Lite Transformer is a general architecture for efficient language applications.

6.4 Amenable to Compression

As an efficient architecture, our Lite Transformer is orthogonal to general techniques for model compression (amenable to compression), *e.g.* pruning, and quantization. The results on WMT'14 En-Fr dataset with those techniques are shown in Table 7. We quantize the model weight into 8 bits with K-means (Han et al., 2016) and prune the model according to the sensitivity of each layer (Han et al., 2015a). With the two model compression techniques, our method achieves 18.2× model size compression with negligible BLEU score degradation.

7 CONCLUSION

In this paper, we presented *Long-Short Range Attention* (LSRA), where some heads focus on the local context modeling while the others capture the long-distance relationship. Based on this primitive, we design *Lite Transformer* (LT) that is specialized for the mobile setting (under 500M Mult-Adds) to facilitate the deployment on the edge devices. Our LT demonstrates consistent improvement over the transformer on multiple language applications. It also surpasses the Evolved Transformer that requires costly architecture search under the mobile setting.

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REFERENCES

Karim Ahmed, Nitish Shirish Keskar, and Richard Socher. Weighted Transformer Network for Machine Translation. *arXiv*, 2017. 3

Alexei Baevski and Michael Auli. Adaptive input representations for neural language modeling. In *ICLR*, 2019. 7, 8, 9

Dzmitry Bahdanau, Kyunghyun Cho, and Yoshua Bengio. Neural Machine Translation by Jointly Learning to Align and Translate. In *ICLR*, 2015. 3

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*, 2019a. 3

Han Cai, Ligeng Zhu, and Song Han. ProxylessNAS: Direct Neural Architecture Search on Target Task and Hardware. In *ICLR*, 2019b. 3

Mia Xu Chen, Orhan Firat, Ankur Bapna, Melvin Johnson, Wolfgang Macherey, George Foster, Llion Jones, Mike Schuster, Noam Shazeer, Niki Parmar, Ashish Vaswani, Jakob Uszkoreit, Lukasz Kaiser, Zhifeng Chen, Yonghui Wu, and Macduff Hughes. The Best of Both Worlds: Combining Recent Advances in Neural Machine Translation. In *ACL*, 2018. 3

Rewon Child, Scott Gray, Alec Radford, and Ilya Sutskever. Generating long sequences with sparse transformers. *arXiv*, 2019. 3

Kevin Clark, Urvashi Khandelwal, Omer Levy, and Christopher D Manning. What Does BERT Look At? An Analysis of BERT's Attention. In *BlackboxNLP*, 2020. 5

Matthieu Courbariaux, Itay Hubara, Daniel Soudry, Ran El-Yaniv, and Yoshua Bengio. Binarized Neural Networks: Training Deep Neural Networks with Weights and Activations Constrained to +1 or -1. *arXiv*, 2016. 3

Jacob Devlin, Ming-Wei Chang, Kenton Lee, and Kristina Toutanova. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. In *NAACL*, 2019. 1

Jonas Gehring, Michael Auli, David Grangier, Denis Yarats, and Yann Dauphin. Convolutional Sequence to Sequence Learning. In *ICML*, 2017. 3, 6

Edouard Grave, Armand Joulin, Moustapha Cissé, Hervé Jégou, et al. Efficient softmax approximation for GPUs. In *ICML*, 2017. 6

Song Han, Jeff Pool, John Tran, and William Dally. Learning both weights and connections for efficient neural network. In *NeurIPS*, 2015a. 9

Song Han, Jeff Pool, John Tran, and William Dally. Learning both Weights and Connections for Efficient Neural Networks. In *NIPS*, 2015b. 3

Song Han, Huizi Mao, and William Dally. Deep Compression: Compressing Deep Neural Networks with Pruning, Trained Quantization and Huffman Coding. In *ICLR*, 2016. 3, 9

Yihui He, Xiangyu Zhang, and Jian Sun. Channel Pruning for Accelerating Very Deep Neural Networks. In *ICCV*, 2017. 3

Yihui He, Ji Lin, Zhijian Liu, Hanrui Wang, Li-Jia Li, and Song Han. AMC: AutoML for Model Compression and Acceleration on Mobile Devices. In *ECCV*, 2018. 3

Karl Moritz Hermann, Tomas Kocisky, Edward Grefenstette, Lasse Espeholt, Will Kay, Mustafa Suleyman, and Phil Blunsom. Teaching machines to read and comprehend. In *NeurIPS*, 2015. 6

Lukasz Kaiser, Aidan N Gomez, and François Chollet. Depthwise Separable Convolutions for Neural Machine Translation. In *ICLR*, 2018. 3

Nal Kalchbrenner, Lasse Espeholt, Karen Simonyan, Aaron van den Oord, Alex Graves, and Koray Kavukcuoglu. Neural Machine Translation in Linear Time. *arXiv*, 2016. 3

Diederik Kingma and Jimmy Ba. Adam: A Method for Stochastic Optimization. In *ICLR*, 2015. 7

Olga Kovaleva, Alexey Romanov, Anna Rogers, and Anna Rumshisky. Revealing the Dark Secrets of BERT. In *EMNLP*, 2019. 5

Raghuraman Krishnamoorthi. Quantizing Deep Convolutional Networks for Efficient Inference: A Whitepaper. *arXiv*, 2018. 3

Mike Lewis, Yinhan Liu, Naman Goyal, Marjan Ghazvininejad, Abdelrahman Mohamed, Omer Levy, Veselin Stoyanov, and Luke Zettlemoyer. BART: Denoising sequence-to-sequence pre-training for natural language generation, translation, and comprehension. *arXiv*, 2019. 6

Chin-Yew Lin. ROUGE: A package for automatic evaluation of summaries. In *Text Summarization Branches Out*. ACL, 2004. 6

Chenxi Liu, Barret Zoph, Maxim Neumann, Jonathon Shlens, Wei Hua, Li-Jia Li, Li Fei-Fei, Alan Yuille, Jonathan Huang, and Kevin Murphy. Progressive Neural Architecture Search. In *ECCV*, 2018. 6

Zechun Liu, Haoyuan Mu, Xiangyu Zhang, Zichao Guo, Xin Yang, Tim Kwang-Ting Cheng, and Jian Sun. MetaPruning: Meta Learning for Automatic Neural Network Channel Pruning. *arXiv*, 2019. 3

Zhuang Liu, Jianguo Li, Zhiqiang Shen, Gao Huang, Shoumeng Yan, and Changshui Zhang. Learning Efficient Convolutional Networks through Network Slimming. In *ICCV*, 2017. 3

Ilya Loshchilov and Frank Hutter. SGDR: Stochastic Gradient Descent with Warm Restarts. In *ICLR*, 2017. 7

Minh-Thang Luong, Hieu Pham, and Christopher Manning. Effective Approaches to Attention-based Neural Machine Translation. In *EMNLP*, 2015. 3

Myle Ott, Sergey Edunov, David Grangier, and Michael Auli. Scaling Neural Machine Translation. In *WMT*, 2018. 3, 8

Myle Ott, Sergey Edunov, Alexei Baevski, Angela Fan, Sam Gross, Nathan Ng, David Grangier, and Michael Auli. fairseq: A Fast, Extensible Toolkit for Sequence Modeling. In *NAACL Demo*, 2019. 7

Romain Paulus, Caiming Xiong, and Richard Socher. A Deep Reinforced Model for Abstractive Summarization. In *ICLR*, 2018. 3

Gabriel Pereyra, George Tucker, Jan Chorowski, Lukasz Kaiser, and Geoffrey Hinton. Regularizing neural networks by penalizing confident output distributions. In *ICLR Workshop*, 2017. 8

Hieu Pham, Melody Y Guan, Barret Zoph, Quoc V Le, and Jeff Dean. Efficient Neural Architecture Search via Parameter Sharing. In *ICML*, 2018. 3

Rico Sennrich, Barry Haddow, and Alexandra Birch. Neural Machine Translation of Rare Words with Subword Units. In *ACL*, 2016. 6

Peter Shaw, Jakob Uszkoreit, and Ashish Vaswani. Self-Attention with Relative Position Representations. In *NAACL*, 2018. 3

David So, Quoc Le, and Chen Liang. The Evolved Transformer. In *ICML*, 2019. 1, 2, 3, 4, 8

Emma Strubell, Ananya Ganesh, and Andrew McCallum. Energy and Policy Considerations for Deep Learning in NLP. In *ACL*, 2019. 8

Sainbayar Sukhbaatar, Edouard Grave, Piotr Bojanowski, and Armand Joulin. Adaptive Attention Span in Transformers. In *ACL*, 2019a. 3

Sainbayar Sukhbaatar, Edouard Grave, Guillaume Lample, Herve Jegou, and Armand Joulin. Augmenting self-attention with persistent memory. *arXiv*, 2019b. 3

Ilya Sutskever, Oriol Vinyals, and Quoc V Le. Sequence to Sequence Learning with Neural Networks. In *NeurIPS*, 2014. 3, 7

Christian Szegedy, Vincent Vanhoucke, Sergey Ioffe, Jon Shlens, and Zbigniew Wojna. Rethinking the inception architecture for computer vision. In *CVPR*, 2016. 8

Mingxing Tan, Bo Chen, Ruoming Pang, Vijay Vasudevan, Mark Sandler, Andrew Howard, and Quoc V Le. MnasNet: Platform-Aware Neural Architecture Search for Mobile. *arXiv*, 2018. 3

Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N Gomez, Lukasz Kaiser, and Illia Polosukhin. Attention is All you Need. In *NeurIPS*, 2017. 1, 3, 4, 5, 6, 7, 8, 9

Kuan Wang, Zhijian Liu, Yujun Lin, Ji Lin, and Song Han. HAQ: Hardware-Aware Automated Quantization with Mixed Precision. In *CVPR*, 2019. 3

Xiaolong Wang, Ross Girshick, Abhinav Gupta, and Kaiming He. Non-local Neural Networks. In *CVPR*, 2018. 3, 4

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*, 2019a. 3

Felix Wu, Angela Fan, Alexei Baevski, Yann Dauphin, and Michael Auli. Pay Less Attention with Lightweight and Dynamic Convolutions. In *ICLR*, 2019b. 2, 3, 5, 6, 7, 8

Yonghui Wu, Mike Schuster, Zhifeng Chen, Quoc V Le, Mohammad Norouzi, Wolfgang Macherey, Maxim Krikun, Yuan Cao, Qin Gao, Klaus Macherey, Jeff Klingner, Apurva Shah, Melvin Johnson, Xiaobing Liu, Stephan Gouws, Yoshikiyo Kato, Taku Kudo, Hideto Kazawa, Keith Stevens, George Kurian, Nishant Patil, Wei Wang, Cliff Young, Jason Smith, Jason Riesa, Alex Rudnick, Oriol Vinyals, Greg Corrado, Macduff Hughes, and Jeffrey Dean. Google's Neural Machine Translation System: Bridging the Gap between Human and Machine Translation. *arXiv*, 2016. 3

Tien-Ju Yang, Andrew Howard, Bo Chen, Xiao Zhang, Alec Go, Mark Sandler, Vivienne Sze, and Hartwig Adam. NetAdapt: Platform-Aware Neural Network Adaptation for Mobile Applications. In *ECCV*, 2018. 3

Chenzhuo Zhu, Song Han, Huizi Mao, and William Dally. Trained Ternary Quantization. In *ICLR*, 2017. 3

Barret Zoph and Quoc V Le. Neural Architecture Search with Reinforcement Learning. In *ICLR*, 2017. 1, 3

Barret Zoph, Vijay Vasudevan, Jonathon Shlens, and Quoc V Le. Learning Transferable Architectures for Scalable Image Recognition. In *CVPR*, 2018. 3