

TINYBERT: **DISTILLING** BERT FOR NATURAL LANGUAGE UNDERSTANDING

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ABSTRACT

Language model pre-training, such as BERT, has significantly improved the performances of many natural language processing tasks. However, pre-trained language models are usually computationally expensive and memory intensive, so it is difficult to effectively execute them on some resource-restricted devices. To accelerate inference and reduce model size while maintaining accuracy, we firstly propose a novel *transformer distillation* method that is a specially designed knowledge distillation (KD) method for transformer based models. By leveraging this new KD method, the plenty of knowledge encoded in a large “teacher” BERT can be well transferred to a small “student” TinyBERT. Moreover, we introduce a new two-stage learning framework for TinyBERT, which performs *transformer distillation* at both the pre-training and task-specific learning stages. This framework ensures that TinyBERT can capture both the general-domain and task-specific knowledge of the teacher BERT.

TinyBERT¹ is empirically effective and achieves comparable results with BERT in GLUE datasets, while being **7.5x smaller** and **9.4x faster** on inference. TinyBERT is also significantly better than state-of-the-art baselines, even with only **~28%** parameters and **~31%** inference time of baselines.

1 INTRODUCTION

Pre-training language models then fine-tuning on downstream tasks has become a new paradigm for natural language processing (NLP). Pre-trained language models (PLMs), such as BERT (Devlin et al., 2018), XLNet (Yang et al., 2019), RoBERTa (Liu et al., 2019) and SpanBERT (Joshi et al., 2019), have achieved great success in many NLP tasks (e.g., the GLUE benchmark (Wang et al., 2018) and the challenging multi-hop reasoning tasks (Ding et al., 2019)). However, PLMs usually have extremely large number of parameters and need long inference time, which are difficult to be deployed on edge devices such as mobile phones. Moreover, recent studies (Wu et al., 2019a) also demonstrate that there is redundancy in PLMs. Therefore, it is crucial and possible to reduce the computational overhead and model storage of PLMs.

There are many model compression techniques (Han et al., 2015a) have been proposed to accelerate deep model inference and reduce model size while maintaining accuracy. The most commonly used techniques include quantization (Gong et al., 2014), weights pruning (Han et al., 2015b), and knowledge distillation (KD) (Romero et al., 2014). In this paper we focus on knowledge distillation, a concept proposed by Hinton et al. (2015) in a *teacher-student* framework. KD aims to transfer the knowledge embedded in a large teacher network to a small student network. The student network is trained to reproduce the behaviors of the teacher network. We propose a novel distillation method for transformer models (Vaswani et al., 2017), and use BERT as an example to investigate the KD methods for large scale PLMs.

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¹Our code and models will be made publicly available.

KD has been extensively studied in NLP (Kim & Rush, 2016; Hu et al., 2018), while designing KD methods for BERT has been rarely explored. The *pre-training-then-fine-tuning* paradigm firstly pre-trains BERT on a large scale unsupervised text corpus, then fine-tunes it on task-specific dataset, which greatly increases the difficulty of BERT distillation. Thus we are required to design more effective KD methods for both stages. To build a competitive TinyBERT, we firstly propose a new *transformer distillation* method to transfer the knowledge embedded in intermediate layers, which includes *attention*, *hidden state*, and *embedding based distillation*. The attention based distillation is inspired by the recent findings (Clark et al., 2019) that the attention weights learned by BERT can capture substantial linguistic knowledge, which is essential to natural language understand. The attention based distillation ensures that the linguistic knowledge can be well transferred from teacher BERT to student TinyBERT, however it is ignored in existing KD methods of BERT, such as *Distilled BiLSTM_{SOFT}* (Tang et al., 2019), *BERT-PKD* (Sun et al., 2019) and *DistilBERT*². Then, we propose a novel *two-stage learning* framework including the *general distillation* and the *task-specific distillation*. At the general distillation stage, the original BERT without fine-tuning acts as the teacher model. The student TinyBERT learns to *mimic* the teacher’s behavior by executing the proposed transformer distillation on the large scale corpus from general domain. We obtain a general TinyBERT that can be fine-tuned for various downstream tasks. At the task-specific distillation stage, we re-execute the transformer distillation on *domain-specific data* to further improve the performance of TinyBERT on downstream tasks. Both the two stages are essential to improve the performance and generalization capability of TinyBERT. A detailed comparison between the proposed method and other existing methods is summarized in Table 1. The transformer distillation and two-stage learning framework are two key ideas of the proposed method.

Table 1: A summary of KD methods for BERT. Abbreviations: INIT(initializing student BERT with some layers of pre-trained BERT), KD_{pre-train}(performing knowledge distillation at pre-training stage), KD_{fine-tune}(performing knowledge distillation at fine-tuning stage), DA(conducting data augmentation for task-specific training data), [CLS](a special classification token of BERT). attention, hidden, embed, and prediction represent the knowledge from attention matrices, hidden states, embedding layers, and final prediction layers, respectively.

KD Methods	At Pre-training Stage		At Fine-tuning Stage	
	INIT	KD _{pre-train}	KD _{fine-tune}	DA
Distilled BiLSTM _{SOFT}			✓ (prediction)	✓
BERT-PKD	✓		✓ ([CLS]+prediction) ³	
DistilBERT	✓	✓ (prediction) ⁴	✓ (prediction)	
TinyBERT (our method)		✓ (embed+hidden+attention)	✓ (embed+hidden+attention+prediction)	✓

The main contributions of this work are as follows: 1) We propose a new transformer distillation method to ensure that the linguistic knowledge encoded in teacher BERT can be well transferred to TinyBERT. 2) We propose a novel two-stage learning framework with performing the proposed transformer distillation at both the pre-training and fine-tuning stages, which ensure that TinyBERT can capture both the general-domain and task-specific knowledge of the teacher BERT. 3) We show experimentally that our TinyBERT can achieve comparable results with teacher BERT on GLUE tasks, while using fewer parameters ($\sim 13.3\%$) and less inference time ($\sim 10.6\%$), and significantly outperforms other state-of-the-art baselines.

2 PRELIMINARIES

We firstly describe the formulation of Transformer (Vaswani et al., 2017) and Knowledge Distillation (Hinton et al., 2015). Our proposed transformer distillation is a specially designed KD method for transformer models.

²<https://github.com/huggingface/pytorch-transformers/tree/master/examples/distillation>

³In BERT-PKD, the student network learns from the [CLS] representation and predictions of the teacher.

⁴DistilBERT uses the outputs of pre-training tasks such as dynamic masking as the supervision signal.

2.1 TRANSFORMER LAYER

Most of recent pre-trained language models (e.g., BERT, XLNet and RoBERTa) are built with transformer layers, which can capture long-term dependencies between input tokens by self-attention mechanism. Specifically, a standard transformer layer includes two main sub-layers: multi-head attention (MHA) and fully connected feed-forward network (FFN).

Multi-Head Attention (MHA). The calculation of attention function depends on the three components of queries, keys and values, which are denoted as matrices \mathbf{Q} , \mathbf{K} and \mathbf{V} respectively. Following, the attention function can be formulated as follows:

$$\mathbf{A} = \frac{\mathbf{Q}\mathbf{K}^T}{\sqrt{d_k}}, \quad (1)$$

$$\text{Attention}(\mathbf{Q}, \mathbf{K}, \mathbf{V}) = \text{softmax}(\mathbf{A})\mathbf{V}, \quad (2)$$

where d_k is the dimension of keys and acts as a scaling factor, \mathbf{A} is the attention matrix calculated from the compatibility of \mathbf{Q} and \mathbf{K} by dot-product operation. The final function output is calculated as a weighted sum of values \mathbf{V} , and the weight is computed by applying $\text{softmax}()$ operation on the matrix \mathbf{A} . The attention matrices \mathbf{A} of BERT can capture substantial linguistic knowledge and plays an essential role in our proposed distillation method.

Multi-head attention is defined by concatenating the attention heads from different representation subspaces as follows:

$$\text{MultiHead}(\mathbf{Q}, \mathbf{K}, \mathbf{V}) = \text{Concat}(\text{head}_1, \dots, \text{head}_h)\mathbf{W}, \quad (3)$$

where h is the number of attention heads, and head_i denotes the i -th attention head, which is calculated by the $\text{Attention}()$ function with inputs from different representation subspaces, the matrix \mathbf{W} acts as a linear transformation.

Position-wise Feed-Forward Network (FFN). Transformer layer also contains a fully connected feed-forward network, which is formulated as follows:

$$\text{FFN}(x) = \max(0, x\mathbf{W}_1 + b_1)\mathbf{W}_2 + b_2. \quad (4)$$

We can see that the FFN contains two linear transformations and one ReLU activation.

2.2 KNOWLEDGE DISTILLATION

KD aims to transfer the knowledge of a large teacher network T to a small student network S . The student network is trained to mimic the behaviors of teacher networks. Let f^T and f^S represent the behavior functions of teacher and student networks, respectively. The behavior function targets at transforming network inputs to some informative representations, and it can be defined as the output of any layer of networks. In the context of transformer distillation, the output of MHA layer or FFN layer, or some intermediate representations (e.g. the attention matrix \mathbf{A}) can be used as behavior function. Formally, KD can be modeled as minimizing the following objective function:

$$\mathcal{L}_{\text{KD}} = \sum_{x \in \mathcal{X}} L(f^S(x), f^T(x)), \quad (5)$$

where $L(\cdot)$ is a loss function that evaluates the difference between teacher and student networks, x is the text input and \mathcal{X} denotes the training dataset. Thus the key research problem is how to define effective behaviors and loss functions. Different from previous KD methods, we also need to consider how to perform KD at the pre-training stage of BERT, which further increases the difficulty of KD for BERT.

3 METHOD

In this section, we propose a novel distillation method for transformer models, then present a two-stage learning framework of TinyBERT.

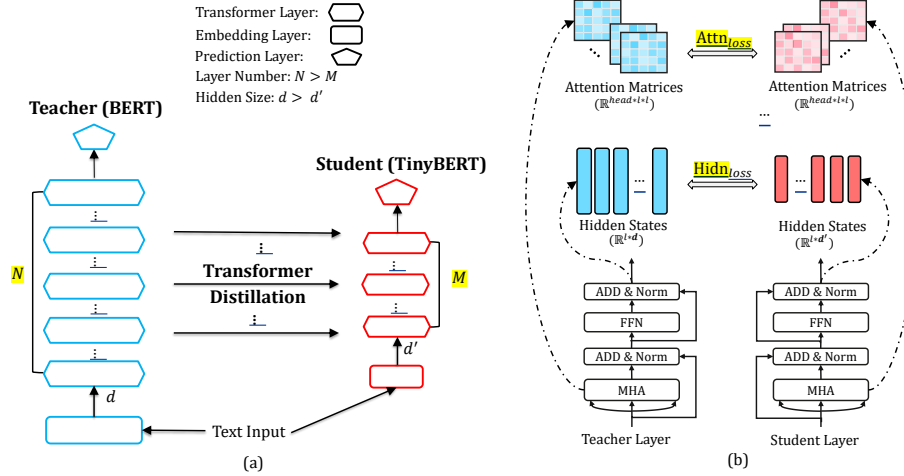


Figure 1: An overview of transformer distillation: (a) the framework of transformer distillation, (b) the details of transformer-layer distillation consisting of Attn_{loss} (attention based distillation) and Hidn_{loss} (hidden states based distillation).

3.1 TRANSFORMER DISTILLATION

The proposed *transformer distillation* is a specially designed KD method for transformer networks. Figure 1 displays an overview of the proposed KD method. In this work, both the student and teacher networks are built with transformer layers. For a clear illustration, we firstly formulate the problem before introducing our method.

Problem Formulation. Assuming that the student model has M transformer layers and teacher model has N transformer layers, we choose M layers from the teacher model for the *transformer-layer distillation*. The function $n = g(m)$ is used as a mapping function from student layers to teacher layers, which means that the m -th layer of student model learns the information from the n -th layer of teacher model. The *embedding-layer distillation* and the *prediction-layer distillation* are also considered. We set 0 to be the index of embedding layer and $M+1$ to be the index of prediction layer, and the *corresponding layer mappings* are defined as $0 = g(0)$ and $N+1 = g(M+1)$ respectively. The effect of the choice of different mapping function on the performances will be studied in the experiment section. Formally, the student can acquire knowledge from the teacher by minimizing the following objective:

$$\mathcal{L}_{\text{model}} = \sum_{m=0}^{M+1} \lambda_m \mathcal{L}_{\text{layer}}(S_m, T_{g(m)}), \quad (6)$$

where $\mathcal{L}_{\text{layer}}$ refers to the loss function of a given model layer (e.g., transformer layer or embedding layer) and λ_m is the hyper-parameter that represents the importance of the m -th layer's distillation.

Transformer-layer Distillation. The proposed transformer-layer distillation includes the *attention based distillation* and *hidden states based distillation*, which is shown in Figure 1 (b). The attention based distillation is motivated by the recent findings that attention weights learned by BERT can capture rich linguistic knowledge (Clark et al., 2019). This kind of linguistic knowledge includes the syntax and coreference information, that offers the essential abilities to understand natural language. Thus we propose the attention based distillation to ensure that the linguistic knowledge is transferred from teacher BERT to student TinyBERT. Specifically, the student learns to fit the attention matrices of multi-head attention from the teacher, and the objective is defined as:

$$\mathcal{L}_{\text{attn}} = \frac{1}{h} \sum_{i=1}^h \text{MSE}(\mathbf{A}_i^S, \mathbf{A}_i^T), \quad (7)$$

where h is the number of attention heads, $\mathbf{A}_i \in \mathbb{R}^{l \times l}$ refers to the attention matrix corresponding to the i -th head of teacher or student, l is the input text length, and $\text{MSE}()$ means the *mean squared*

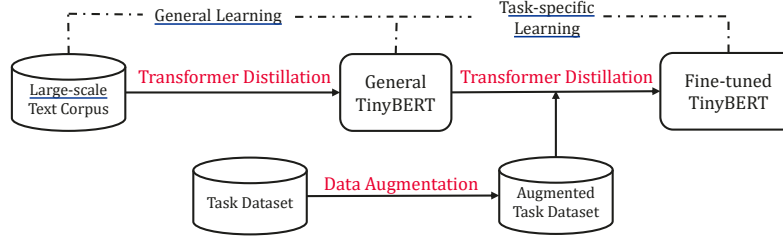


Figure 2: The illustration of TinyBERT learning

error loss function. In this work, the attention matrix \mathbf{A}_i is used as the fitting target instead of its softmax output $\text{softmax}(\mathbf{A}_i)$, since our experiments show that this setting has faster convergence and better performances.

In addition to attention based distillation, we also distill the knowledge from the output of transformer layer (as shown in Figure 1 (b)), and the objective is as follows:

$$\mathcal{L}_{\text{hidn}} = \text{MSE}(\mathbf{H}^S \mathbf{W}_h, \mathbf{H}^T), \quad (8)$$

where the matrices $\mathbf{H}^S \in \mathbb{R}^{l \times d'}$ and $\mathbf{H}^T \in \mathbb{R}^{l \times d}$ refer to the hidden states of student and teacher networks respectively, which are calculated by Equation 4. The scalar values d and d' denote the hidden sizes of teacher and student models, and d' is often smaller than d to obtain a smaller student network. The matrix $\mathbf{W}_h \in \mathbb{R}^{d' \times d}$ is a learnable linear transformation, which transforms the hidden states of student network into the same space as teacher network's states.

Embedding-layer Distillation. We also perform embedding-layer distillation, which is similar to the hidden states based distillation and formulated as:

$$\mathcal{L}_{\text{emb}} = \text{MSE}(\mathbf{E}^S \mathbf{W}_e, \mathbf{E}^T), \quad (9)$$

where the matrices \mathbf{E}^S and \mathbf{E}^T refer to the embeddings of student and teacher networks, respectively. In this paper, they have the same shape as the hidden state matrices. The matrix \mathbf{W}_e is a linear transformation playing a similar role as \mathbf{W}_h .

Prediction-Layer Distillation. In addition to imitating the behaviors of intermediate layers, we also use the knowledge distillation to fit the predictions of teacher model (Hinton et al., 2015). Specifically, we penalize the soft cross-entropy loss between the student network's logits against the teacher's logits:

$$\mathcal{L}_{\text{pred}} = -\text{softmax}(\mathbf{z}^T) \cdot \log_{\text{softmax}}(\mathbf{z}^S / t), \quad (10)$$

where \mathbf{z}^S and \mathbf{z}^T are the logits vectors predicted by the student and teacher respectively, $\log_{\text{softmax}}()$ means the log likelihood, t means the temperature value. In our experiment, we find that $t = 1$ performs well.

Using the above distillation objectives (i.e. Equations 7, 8, 9 and 10), we can unify the loss of model layer:

$$\mathcal{L}_{\text{layer}}(S_m, T_{g(m)}) = \begin{cases} \mathcal{L}_{\text{emb}}(S_0, T_0), & m = 0 \\ \mathcal{L}_{\text{hidn}}(S_m, T_{g(m)}) + \mathcal{L}_{\text{attn}}(S_m, T_{g(m)}), & M \geq m > 0 \\ \mathcal{L}_{\text{pred}}(S_{M+1}, T_{N+1}), & m = M + 1 \end{cases} \quad (11)$$

In our experiments, we firstly perform *intermediate layer distillation* ($M \geq m \geq 0$), then perform the *prediction-layer distillation* ($m = M + 1$).

3.2 TINYBERT LEARNING

The application of BERT usually consists of two learning stages: the pre-training and fine-tuning stages. The plenty of knowledge learned in the pre-training stage should also be well transferred. Therefore, we propose a novel two-stage learning framework including the *general distillation* and the *task-specific distillation*, as illustrated in Figure 2. General distillation helps student TinyBERT

Table 2: GLUE test results that are scored by the GLUE evaluation server. All models are learned in a single-task manner. “-” means the result is not reported. BERT_{SMALL} means directly pretraining a small BERT, which has the same model architecture as TinyBERT, through tasks of *Masked Language Model* (MLM) and *Next Sentence Prediction* (NSP).

System	MNLI-m	MNLI-mm	QQP	SST-2	QNLI	MRPC	RTE	CoLA	STS-B	Average
BERT _{BASE} (Google)	84.6	83.4	71.2	93.5	90.5	88.9	66.4	52.1	85.8	79.6
BERT _{BASE} (Teacher)	83.9	83.4	71.1	93.4	90.9	87.5	67.0	52.8	85.2	79.5
BERT _{SMALL}	75.4	74.9	66.5	87.6	84.8	83.2	62.6	19.5	77.1	70.2
Distilled BiLSTM _{SOFT}	73.0	72.6	68.2	90.7	-	-	-	-	-	-
BERT-PKD	79.9	79.3	70.2	89.4	85.1	82.6	62.3	24.8	79.8	72.6
DistilBERT	78.9	78.0	68.5	91.4	85.2	82.4	54.1	32.8	76.1	71.9
TinyBERT	82.5	81.8	71.3	92.6	87.7	86.4	62.9	43.3	79.9	76.5

learn the rich linguistic knowledge embedded in teacher BERT, which plays an important role in improving the generalization capability of TinyBERT. The task-specific distillation teaches the student task-specific knowledge. With this two-step distillation, we can further reduce the gap between teacher and student networks.

General Distillation. In general distillation, we use the original BERT without fine-tuning as the teacher and a large-scale text corpus as the basic learning material. By performing the transformer distillation⁵ on the text from general domain, we obtain a general TinyBERT that can be fine-tuned for downstream tasks. However, due to the big reductions in the hidden/embedding size and the layer number, general TinyBERT performs relatively worse than the original BERT.

Task-specific Distillation. Previous studies show that the complex models, fine-tuned BERTs, suffer from over-parameterization in domain-specific tasks (Wu et al., 2019a). Thus, it is possible for small models to achieve comparable performances to big BERTs. To this end, we propose to derive competitive fine-tuned TinyBERTs through the task-specific distillation. In the task-specific distillation, we re-perform the proposed transformer distillation on augmented task-specific dataset (as shown in Figure 2). Specifically, the fine-tuned big BERT is used as the teacher and a new data augmentation method is proposed to extend the task-specific training set. With learning more task-related materials, the generalization capabilities of student model can be further improved. In this work, we combine a pre-trained language model BERT and GloVe (Pennington et al., 2014) word embeddings to do word-level replacement for data augmentation. Specifically, we use the language model to predict word replacements for single-piece words (Wu et al., 2019b), and use the word embeddings to retrieve the most similar words as word replacements for multiple-pieces words. Some hyper-parameters are defined to control the replacement ratio of a sentence and the amount of augmented dataset. More details of data augmentation procedure are discussed in Appendix A.

The above two learning stages are complementary to each other: the general distillation provides a good initialization for the task-specific distillation, while the task-specific distillation further improves TinyBERT by focusing on learning the task-specific knowledge. Although there is a big gap between BERT and TinyBERT in model size, by performing the proposed two-stage distillation, the TinyBERT can achieve comparable performances as large BERT in various NLP tasks. The proposed *transformer distillation* and *two-stage learning framework* are the two most important components of the proposed distillation method.

4 EXPERIMENTS

In this section, we evaluate the effectiveness and efficiency of TinyBERT on a variety of tasks with different model settings.

4.1 MODEL SETUP

We instantiate a tiny student model (the number of layers $M=4$, the hidden size $d'=312$, the feed-forward/filter size $d'_i=1200$ and the head number $h=12$) that has a total of 14.5M parameters. If not specified, this student model is referred to as the TinyBERT. The original BERT_{BASE} (the number of layers $N=12$, the hidden size $d=768$, the feed-forward/filter size $d_i=3072$ and the head number

⁵In the general distillation, we do not perform prediction-layer distillation as Equation 10.

Table 3: The model sizes and inference time for baselines and TinyBERT. The number of layers does not include the embedding and prediction layers.

System	Layers	Hidden Size	Feed-forward Size	Model Size	Inference Time
BERT _{BASE} (Teacher)	12	768	3072	109M($\times 1.0$)	188s($\times 1.0$)
Distilled BiLSTM _{SOFT}	1	300	400	10.1M($\times 10.8$)	24.8s($\times 7.6$)
BERT-PKD/DistilBERT	4	768	3072	52.2M($\times 2.1$)	63.7s($\times 3.0$)
TinyBERT	4	312	1200	14.5M($\times 7.5$)	19.9s($\times 9.4$)

Table 4: Results of wider or deeper TinyBERT variants and baselines.

System	MNLI-m	MNLI-mm	MRPC	CoLA	Average
BERT _{BASE} (Teacher)	84.2	84.4	86.8	57.4	78.2
BERT-PKD ($M=6; d'=768; d'_i=3072$)	80.9	80.9	83.1	43.1	72.0
DistilBERT ($M=6; d'=768; d'_i=3072$)	81.6	81.1	82.4	42.5	71.9
TinyBERT ($M=4; d'=312; d'_i=1200$)	82.8	82.9	85.8	49.7	75.3
TinyBERT ($M=4; d'=768; d'_i=3072$)	83.8	84.1	85.8	50.5	76.1
TinyBERT ($M=6; d'=312; d'_i=1200$)	83.3	84.0	86.3	50.6	76.1
TinyBERT ($M=6; d'=768; d'_i=3072$)	84.5	84.5	86.3	54.0	77.3

$h=12$) is used as the teacher model that contains 109M parameters. We use $g(m) = 3 \times m$ as the layer mapping function, so TinyBERT learns from every 3 layers of BERT_{BASE}. The learning weight λ of each layer is set to 1, which performs well for the learning of our TinyBERT.

4.2 EXPERIMENTAL RESULTS ON GLUE

We evaluate TinyBERT on the General Language Understanding Evaluation (GLUE) (Wang et al., 2018) benchmark, which is a collection of diverse natural language understanding tasks. The details of experiment settings are described in Appendix B. The evaluation results are presented in Table 2 and the efficiencies of model size and inference time are also evaluated in Table 3.

The experiment results demonstrate that: 1) There is a large performance gap between BERT_{SMALL} and BERT_{BASE} due to the big reduction in model size. 2) TinyBERT is consistently better than BERT_{SMALL} in all the GLUE tasks and achieves a large improvement of 6.3% on average. This indicates that the proposed KD learning framework can effectively improve the performances of small models regardless of downstream tasks. 3) TinyBERT significantly outperforms the state-of-the-art KD baselines (i.e., BERT-PKD and DistilBERT) by a margin of at least 3.9%, even with only $\sim 28\%$ parameters and $\sim 31\%$ inference time of baselines (see Table 3). 4) Compared with the teacher BERT_{BASE}, TinyBERT is 7.5x smaller and 9.4x faster in the model efficiency, while maintaining comparable performances. 5) TinyBERT has a comparable model efficiency (slightly larger in size but faster in inference) with Distilled BiLSTM_{SOFT} and obtains substantially better performances in all tasks reported by the BiLSTM baseline. 6) For the challenging CoLA dataset (the task of predicting linguistic acceptability judgments), all the distilled small models have a relatively bigger performance gap with teacher model. TinyBERT achieves a significant improvement over the strong baselines, and its performance can be further improved by using a deeper and wider model to capture more complex linguistic knowledge as illustrated in the next subsection.

Moreover, BERT-PKD and DistilBERT initialize their student models with some layers of well pre-trained teacher BERT (see Table 1), which makes the student models have to keep the same size settings of transformer-layer (or embedding-layer) as their teacher BERT. In our two-stage distillation framework, TinyBERT is initialized by general distillation, so it has the advantage of being more flexible in model size selection.

4.3 EFFECTS OF MODEL SIZE

We evaluate how much improvement can be achieved when increasing the model size of TinyBERT on four typical GLUE tasks, where MNLI and MRPC are used in the ablation studies of Devlin et al. (2018), and CoLA is the most difficult task in GLUE. Specifically, three wider and deeper variants are proposed and their evaluation results on development set are displayed in Table 4. We can observe that: 1) All the three TinyBERT variants can consistently outperform the original smallest

Table 5: Ablation studies of different procedures (i.e., TD, GD, and DA) of the two-stage learning framework.

System	MNLI-m 392k	MNLI-mm 392k	MRPC 3.5k	CoLA 8.5k	Average
TinyBERT	82.8	82.9	85.8	49.7	75.3
No GD	82.5	82.6	84.1	40.8	72.5
No TD	80.6	81.2	83.8	28.5	68.5
No DA	80.5	81.0	82.4	29.8	68.4

Table 6: Ablation studies of different distillation objectives in the TinyBERT learning. The variants are validated on the dev set.

System	MNLI-m	MNLI-mm	MRPC	CoLA	Average
TinyBERT	82.8	82.9	85.8	49.7	75.3
No Emb	82.3	82.3	85.0	46.7	74.1
No Trm	71.7	72.3	70.1	11.2	56.3
No Attn	79.9	80.7	82.3	41.1	71.0
No Hidn	81.7	82.1	84.1	43.7	72.9

Table 7: Results (dev) of different mapping strategies.

System	MNLI-m	MNLI-mm	MRPC	CoLA	Average
TinyBERT (Uniform-strategy)	82.8	82.9	85.8	49.7	75.3
TinyBERT (Top-strategy)	81.7	82.3	83.6	35.9	70.9
TinyBERT (Bottom-strategy)	80.6	81.3	84.6	38.5	71.3

TinyBERT, which indicates that the proposed KD method works for the student models of various model sizes. 2) For the CoLA task, the improvement is slight when only increasing the number of layers (from 49.7 to 50.6) or hidden size (from 49.7 to 50.5). To achieve more dramatic improvements, the student model should become deeper and wider (from 49.7 to 54.0). 3) Another interesting observation is that the smallest 4-layer TinyBERT can even outperform the 6-layers baselines, which further conforms the effectiveness of the proposed KD method.

4.4 ABLATION STUDIES

In this section, we conduct ablation studies to investigate the contributions of : 1) different procedures of the proposed two-stage TinyBERT learning framework (see Figure 2), and 2) different distillation objectives of intermediate layer distillation (see Equations 7, 8, 9).

Effects of different learning procedures. The proposed two-stage TinyBERT learning framework (see Figure 2) consists of three key procedures: TD (Task-specific Distillation), GD (General Distillation) and DA (Data Augmentation). The effects of different learning procedures are analyzed and presented in Table 5. The results indicate that all the three procedures are crucial for the proposed KD method. The TD and DA has comparable effects in all the four tasks. We can also find the task-specific procedures (TD and DA) are more helpful than the pre-training procedure (GD) in all the four tasks. Another interesting observation is that GD has more effect on CoLA than on MNLI and MRPC. We conjecture that the ability of linguistic generalization (Warstadt et al., 2018) learned by GD plays a more important role in the downstream CoLA task (linguistic acceptability judgments).

Effects of different distillation objectives. We investigate the effects of intermediate layer distillation on the TinyBERT learning. Several baselines are proposed including the TinyBERT learning without the transformer-layer distillation (No Trm) and embedding-layer distillation (No Emb) respectively. The results are illustrated in Table 6 and show that all the proposed distillation objectives are useful for the TinyBERT learning. The performance drops significantly from 75.3 to 56.3 under the setting (No Trm), which indicates transformer-layer distillation is the key for TinyBERT learning. Furthermore, we study the contributions of attention (No Attn) and hidden states (No Hidn) in the transformer-layer distillation. We can find the attention based distillation has a bigger effect than hidden states based distillation on TinyBERT learning. Meanwhile, these two kinds of knowledge distillation are complementary to each other, which makes TinyBERT obtain the competitive results.

4.5 EFFECTS OF MAPPING FUNCTION

We investigate the effects of different mapping functions $n = g(m)$ on the TinyBERT learning. Our original TinyBERT as described in section 4.1 uses the uniform-strategy, and we compare with two typical baselines including top-strategy ($g(m) = m + N - M; 0 < m < M$) and bottom-strategy ($g(m) = m; 0 < m \leq M$).

The comparison results are presented in Table 7. We find that the top-strategy performs better than the bottom-strategy in MNLI, while being worse in MRPC and CoLA tasks, which confirms the

observations that different tasks depend on the different kinds of knowledge from BERT layers. Since the uniform-strategy acquires the knowledge from bottom to top layers of BERT_{BASE}, it achieves better performances than the other two baselines in all the four tasks. Adaptively choosing layers for a specific task is a challenging problem and we leave it as the future work.

Other Experiments. We also evaluate TinyBERT on the question answering tasks, and study whether we can use BERT_{SMALL} as the initialization of the general TinyBERT. The experiments are detailed in Appendix C and D.

5 CONCLUSION AND FUTURE WORK

In this paper, we firstly introduce a new KD method for transformer-based distillation, then we further propose a two-stage framework for TinyBERT learning. Extensive experiments show that the TinyBERT achieves competitive performances meanwhile significantly reducing the model size and shortening the inference time of original BERT_{BASE}, which provides an effective way to deploy BERT-based NLP applications on the edge devices.

In future work, we would study how to effectively transfer the knowledge from wider and deeper teachers (e.g., BERT_{LARGE} and XLNet_{LARGE}) to student TinyBERT. The joint learning of distillation and quantization/pruning would be another promising direction to further compress the pre-trained language models.

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APPENDIX

A DATA AUGMENTATION DETAILS

In this section, we explain the proposed data augmentation method. Specifically, we firstly mask a word in a sentence, then use BERT as a language model to predict N most-likely words in the corresponding position, while keeping other words unchanged. By this way, we can easily get the candidates for each word under a specific context. To induce new instances for a given sentence, we also use a threshold p_t to determine whether we should replace the current word with a randomly selected candidate. By repetitively performing this replacement operation for each word in a sentence, we can finally get a new augmented sentence. In our preliminary experiments, we find the quality of generated candidates for the words consisting of multiple sub-word pieces, is relatively low. To alleviate this problem, we instead pick a similar word from GloVe (Pennington et al., 2014) word embeddings based on the cosine similarity. We apply this data augmentation method N times to all the sentences of a downstream task. In this work, we set $p_t = 0.4$, $N = 20$ for all our experiments. The data augmentation procedure is illustrated as below:

Algorithm 1 The Proposed Data Augmentation

Input: \mathbf{x} is a sequence of words

p_t, N are hyperparameters

Output: Data_aug, the augmented data

```

1: function DATA_AUGMENTATION( $\mathbf{x}, p_t, N$ )
2:    $n \leftarrow 0$ 
3:   Data_aug  $\leftarrow []$ 
4:   while  $n < N$  do
5:      $\mathbf{x}_{masked} \leftarrow \mathbf{x}$ 
6:     for  $i \leftarrow 1$  to  $len(\mathbf{x})$  do
7:       if  $\mathbf{x}[i]$  is a single-piece word then
8:         Replace  $\mathbf{x}_{masked}[i]$  with [MASK]
9:          $candidates \leftarrow BertModel(\mathbf{x}_{masked})[i]$ 
10:      else
11:         $candidates \leftarrow N$  similar words of  $\mathbf{x}[i]$  from GloVe
12:      end if
13:      Sample  $p \sim UNIFORM(0, 1)$ 
14:      if  $p \leq p_t$  then
15:        Replace  $\mathbf{x}_{masked}[i]$  with a word from  $candidates$  randomly
16:      else
17:        Keep  $\mathbf{x}_{masked}[i]$  as  $\mathbf{x}[i]$  unchanged
18:      end if
19:    end for
20:    Append  $\mathbf{x}_{masked}$  to Data_aug
21:     $n = n + 1$ 
22:  end while
23:  return Data_aug
24: end function

```

B GLUE DETAILS

TinyBERT setup. TinyBERT learning includes the general distillation and the task-specific distillation. For the general distillation, we use English Wikipedia (2,500 M words) as the text corpus and perform the *intermediate layer distillation* for 3 epochs with the supervision from a pre-trained

BERT_{BASE} teacher and keep other hyper-parameters same as BERT pre-training (Devlin et al., 2018). For task-specific distillation, we firstly perform *intermediate layer distillation* on the augmented dataset for 10 epochs with batch size 32 and learning rate 5e-5 under the supervision of a fine-tuned BERT teacher, and then perform *prediction layer distillation* for 3 epochs with batch size 32 and learning rate 3e-5. For tasks like MNLI, QQP and QNLI which have $\geq 100K$ training examples, we distill intermediate layer knowledge for 5 epochs with batch size 256 on the augmented dataset. Besides, for CoLA task, we perform 50 epochs of *intermediate layer distillation*.

Baselines setup. We use BERT-PKD and DistilBERT as our baselines. For a fair comparison, we firstly re-implemented the results of BERT-PKD and DistilBERT reported in their papers to ensure our implementation procedure is correct. Then following the verified implementation procedure, we trained a 4-layer BERT-PKD and a 4-layer DistilBERT as the baselines. The BERT_{SMALL} learning strictly follows the same learning strategy as described in the original BERT work (Devlin et al., 2018).

Model efficiency evaluation. To evaluate the inference speed, we ran inference procedure on the QNLI training set with batch size of 128 and the maximum sequence length of 128. The numbers reported in Table 3 are the average running time of 100 batches on a single NVIDIA K80 GPU.

The GLUE datasets are described as follows:

MNLI. Multi-Genre Natural Language Inference is a large-scale, crowd-sourced entailment classification task (Williams et al., 2018). Given a pair of $\langle \text{premise}, \text{hypothesis} \rangle$, the goal is to predict whether the *hypothesis* is an entailment, contradiction, or neutral with respect to the *premise*.

QQP. Quora Question Pairs is a collection of question pairs from the website Quora. The task is to determine whether two questions are semantically equivalent (Chen et al., 2018).

QNLI. Question Natural Language Inference is a version of the Stanford Question Answering Dataset which has been converted to a binary sentence pair classification task by Wang et al. (2018). Given a pair $\langle \text{question}, \text{context} \rangle$. The task is to determine whether the *context* contains the answer to the *question*.

SST-2. The Stanford Sentiment Treebank is a binary single-sentence classification task, where the goal is to predict the sentiment of movie reviews (Socher et al., 2013).

CoLA. The Corpus of Linguistic Acceptability is a task to predict whether an English sentence is a grammatically correct one (Warstadt et al., 2018).

STS-B. The Semantic Textual Similarity Benchmark is a collection of sentence pairs drawn from news headlines and many other domains (Cer et al., 2017). The task aims to evaluate how similar two pieces of texts are by a score from 1 to 5.

MRPC. Microsoft Research Paraphrase Corpus is a paraphrase identification dataset where systems aim to identify if two sentences are paraphrases of each other (Dolan & Brockett, 2005).

RTE. Recognizing Textual Entailment is a binary entailment task with a small training dataset (Bentivogli et al., 2009).

C SQUAD 1.1 AND 2.0

We also demonstrate the effectiveness of TinyBERT on the question answering (QA) tasks: SQuAD v1.1 (Rajpurkar et al., 2016) and v2.0 (Rajpurkar et al., 2018). Following the learning procedure in the previous work (Devlin et al., 2018), we treat these two tasks as the problem of sequence labeling which predicts the possibility of each token as the start or end of answer span. We follow the settings of task-specific distillation in GLUE tasks, except with 3 running epochs and a learning rate of 5e-5 for the prediction-layer distillation on the original training dataset. The results are shown in Table 8.

The results show that TinyBERT consistently outperforms the baselines in both the small and medium size, which indicates that the proposed framework also works for the tasks of token-level labeling. Compared with sequence-level GLUE tasks, the question answering tasks depends on more subtle knowledge to infer the correct answer, which increases the difficulty of knowledge distillation. We leave how to build a better QA-TinyBERT as the future work.

Table 8: Results (dev) of baselines and TinyBERT on question answering tasks.

System	SQuAD 1.1		SQuAD 2.0	
	EM	F1	EM	F1
BERT _{BASE} (Teacher)	80.7	88.4	73.1	76.4
<i>Small Models</i>				
BERT-PKD($M=4; d'=768; d'_i=3072$)	70.1	79.5	60.8	64.6
DistilBERT($M=4; d'=768; d'_i=3072$)	71.8	81.2	60.6	64.1
TinyBERT($M=4; d'=312; d'_i=1200$)	72.7	82.1	65.3	68.8
<i>Medium-sized Models</i>				
BERT-PKD($M=6; d'=768; d'_i=3072$)	77.1	85.3	66.3	69.8
DistilBERT($M=6; d'=768; d'_i=3072$)	78.1	86.2	66.0	69.5
TinyBERT($M=6; d'=768; d'_i=3072$)	79.7	87.5	69.9	73.4

Table 9: Results of different methods at pre-training state. TD and GD refers to Task-specific Distillation (without data augmentation) and General Distillation. The results are evaluated on development set.

System	MNLI-m (392k)	MNLI-mm (392k)	MRPC (3.5k)	CoLA (8.5k)	Average
BERT _{SMALL} (MLM&NSP)	75.9	76.9	83.2	19.5	63.9
BERT _{SMALL} (MLM&NSP+TD)	79.2	79.7	82.9	12.4	63.6
TinyBERT (GD)	76.6	77.2	82.0	8.7	61.1
TinyBERT (GD+TD)	80.5	81.0	82.4	29.8	68.4

D BERT_{SMALL} AS INITIALIZATION OF GENERAL TINYBERT

Initializing general TinyBERT with BERT_{SMALL} is a straightforward idea. However, BERT_{SMALL} would derive mismatched distributions in intermediate representations (e.g., attention matrices and hidden states) with the teacher BERT_{BASE} model, if without imitating the teacher’s behaviors at the pre-training stage. Further task-specific distillation under the supervision of BERT_{BASE} will disturb the learned distribution/knowledge of BERT_{SMALL}, finally leading to poor performances in some less-data tasks. The results in Table 9, show that the BERT_{SMALL}(MLM&NSP+TD) performs worse than the BERT_{SMALL} in MRPC and CoLA tasks, which validates our hypothesis. For the intensive-data task (e.g. MNLI), TD learning has enough learning materials to make BERT_{SMALL} acquire the task-specific knowledge very well, although the pre-trained distributions have already been disturbed.

To make TinyBERT effectively work for all tasks, we propose General Distillation (GD) for initialization, where the TinyBERT learns the knowledge from intermediate layers of teacher BERT at the pre-training stage. From the results of Table 9, we find that GD can effectively transfer the knowledge from the teacher BERT to the student TinyBERT and achieve comparable results with BERT_{SMALL} (61.1 vs 63.9), even without performing the MLM and NSP tasks. Furthermore, the task-specific distillation boosts the performances of TinyBERT by continuing on learning the task-specific knowledge of fine-tuned teacher BERT_{BASE}.