P-Distill: Efficient and Effective Prompt Tuning using Knowledge Distillation

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Abstract

In the field of natural language processing (NLP), prompt-based learning is widely used for efficient parameter learning. However, this method has the drawback of shortening the input length by the extent of the attached prompt, leading to an inefficiency in utilizing the input space. In this study, we propose P-Distill, a novel prompt compression method that mitigates the aforementioned limitation of prompt-based learning while maintaining performance via knowledge distillation. The knowledge distillation process of P-Distill consists of two methods, namely prompt initialization and prompt distillation. Experiments on various NLP tasks demonstrate that P-Distill exhibits comparable or superior performance compared to other state-of-the-art prompt-based learning methods, even with significantly shorter prompts. Specifically, We achieve a peak improvement of 1.90% even with the prompt lengths compressed to one-eighth. An additional study further provides insights into the distinct impact of each method on the overall performance of P-Distill. Our code will be released upon acceptance.

1 Introduction

Pre-trained language models (PLMs) have been effective in improving performances of various natural language processing (NLP) tasks (Devlin et al., 2019; Brown et al., 2020; Touvron et al., 2023). These models are fine-tuned by optimizing all parameters to enhance the performances of specific downstream tasks; however, fine-tuning requires significant computational resources while training. The need for significant computational resources for storage and training becomes a challenge, especially when fine-tuning large language models such as Llama2 (Touvron et al., 2023), which may not be readily available to most users.

To reduce computational costs, researchers have explored various methods for efficiently fine-tuning the parameters (Houlsby et al., 2019; Hu et al., 2021; Liu et al., 2022). In contrast to the traditional model fine-tuning that updates all parameters for a downstream task, P-tuning v2 (Liu et al., 2022) fixes the pre-trained parameters and only trains the continuous prompts, which are trainable embeddings attached at the beginning or throughout each layer of the model. While P-tuning v2 is computationally efficient, particularly for PLMs with a large number of parameters, it overlooks the inefficiency in utilizing input space by attaching continuous prompts (Hu et al., 2021). This attachment increases the attention computation, thereby requiring truncation of the positional encodings for the attached prompts, which reduces the available input token sequence length. Extending the input token sequence by forcibly modifying the code can lead to issues with attention calculation beyond the model's training (Chen et al., 2023). Such modifications often result in performance degradation, as the attention mechanism might struggle with sequences extending beyond its initially intended scope. Similar to the findings in the work (Liu et al., 2022), more challenging tasks require longer prompt lengths to achieve the better performance, as shown in Figure 1.

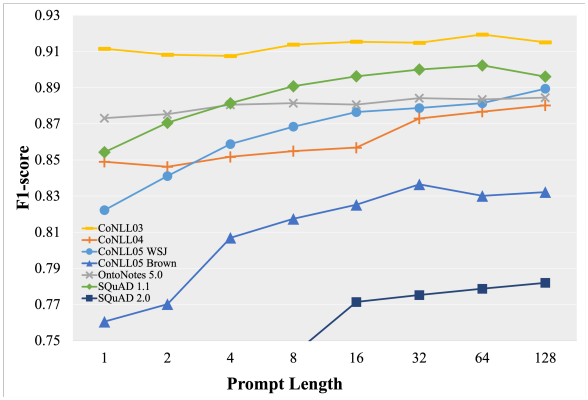


Figure 1: Performance variation in P-tuning v2 across tasks based on the length of continuous prompts.

In this paper, we propose P-Distill, which is a novel prompt compression method to mitigate the limitations of long prompts. Our method involves a two-step process where we first train a teacher model using P-tuning v2 to achieve superior performance with long prompts. We then transfer this knowledge to a student model with significantly shorter prompts through a distillation process. To ensure stability in training, we first perform prompt initialization based on the teacher model prompts. Then, we focus on distilling knowledge between the teacher and student models, specifically targeting the outputs of their intermediate and prediction layers. This is due to the impact of continuous prompts on the hidden states within these layers, which subsequently influences the model's predictions. This method enables the compression of prompts to shorter lengths without a significant degradation in performance, thereby addressing the inefficiencies inherent in longer prompts.

To validate its effectiveness and efficiency, we evaluate P-Distill using various NLP benchmarks. Our results demonstrate that P-Distill exhibits comparable or superior performance than those of the existing state-of-the-art prompt-based models. To the best of our knowledge, this study is the first to train teacher prompts and transfer their knowledge to student prompts for the purpose of compressing prompts. The main contributions of this study are summarized as follows:

- We propose a method called P-Distill to compress the continuous prompts, effectively mitigating the limitation of reducing the model's usable sequence length in prompt-based learning.
- We introduce a prompt distillation method utilizing teacher model's hidden state and prediction outputs, influenced by continuous prompts, and propose a prompt initialization for stable prompt distillation.
- We validate P-Distill across multiple NLP benchmarks, demonstrating its ability to maintain or enhance accuracy while reducing prompt lengths by up to eight times.

The remainder of this paper is structured as follows: Section 2 provides the preliminaries; Section 3 describes a detailed description of the proposed method; Section 4 presents the experimental results and analysis, and Section 5 concludes the study.

2 Preliminaries

2.1 Pre-trained Language Models Based on the Transformer

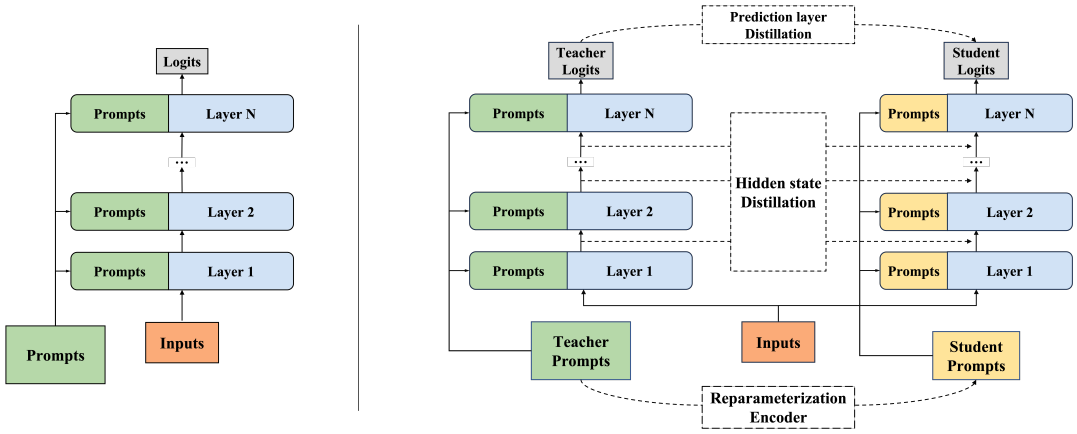
The transformer model (Vaswani et al., 2023), comprising an encoder and decoder, is the fundamental architecture of the majority of recent PLMs, including BERT (Devlin et al., 2019), RoBERTa (Liu et al., 2019), and GPT-3 (Brown et al., 2020). Each encoder and decoder consists of multiple transformer layers and incorporates key components, such as multi-head attention modules (MHA), feed-forward networks, layer normalization, and residual connections. A key component of this architecture is the multi-head attention mechanism, which computes attention weights using query (Q), key (K), and value (V) matrices. Mathematically, the attention function in multi-head attention can be represented as follows:

$$Att(x) = softmax(\frac{QK^T}{\sqrt{d_k}})V, \quad (1)$$

where $\sqrt{d_k}$ is the scaling factor for gradient stabilization during training. This attention mechanism is crucial in understanding language and generating tasks by modulating the focus of the model on different parts of the input data.

2.2 Prompt-based Learning Methods

Prompt-based learning methods have emerged as an efficient alternative to full model fine-tuning, especially for PLMs (Liu et al., 2022, 2023). These methods use prompts to guide the model predictions for specific tasks. Several approaches (Jiang et al., 2020; Shin et al., 2020) employ discrete prompts, which are fixed templates added to the input. For example, in sentiment analysis, a template might be "This text *[Input Text]* expresses a *[MASK]* sentiment.". However, discrete prompts are limited in that their performances significantly depend on template selection. Advanced approaches, such as Prefix-Tuning (Li and Liang, 2021) and P-tuning (Liu et al., 2023), use continuous prompts that are trainable embeddings independent of the model vocabulary. Particularly, P-tuning v2 (Liu et al., 2022) attaches continuous prompts to each layer of the model, thereby influencing its behavior and enhancing its performance in downstream tasks. These continuous prompts are integrated into the attention mechanism of the



(a) P-tuning v2

(b) P-Distill (Ours)

Figure 2: (a) Illustration of P-tuning v2 (Liu et al., 2022). (b) Illustration of the proposed method, denoted as P-Distill. This method trains a teacher model to generate concise and effective prompts, followed by distilling the knowledge into a student model.

transformer model as follows:

$$Att(x) = softmax\left(\frac{Q(P_k : K)^T}{\sqrt{d_k}}\right)(P_v : V), \quad (2)$$

where $P_k \in R^{n_p \times d}$ and $P_v \in R^{n_p \times d}$ are the continuous prompts added to the key and value vectors, respectively, the colon denotes the concatenation of these prompts with the key and value matrices. The dimension n_p indicates the lengths of the prompts, and d represents the dimensions of the key and value vectors. This integration enables the model to influence layers closer to the output, significantly affecting the final predictions.

2.3 Knowledge Distillation

In artificial intelligence, knowledge distillation (KD) is a technique for reducing the size of large models while preserving their performances (Jiao et al., 2020; Sun et al., 2020; Sanh et al., 2020; Hinton et al., 2015). During KD, a smaller student model is trained to internalize and emulate the complex decision-making patterns and behaviors of a larger teacher model. This process involves the behavior functions of the models, f^T and f^S, transforming inputs into informative representations, typically defined as the output of any layer within the model. These representations contain abundant information for model predictions. KD is quantified using loss functions, such as the Kullback-Leibler divergence (Kullback and Leibler, 1951) or Mean Squared Error (MSE) (Hinton et al., 2015), as follows:

$$L_{KD} = \sum_{x \in X} L(f^S(x), f^T(x)), \quad (3)$$

where x is the input, and X and L denote the dataset and the loss function, respectively. This approach enables the student model to gain a comprehensive understanding of various classes, enhancing its application in fields such as NLP.

3 Methodology

Many existing prompt tuning methods, including P-tuning v2, have the drawback of occupying an unnecessarily large portion of the input token space owing to their long prompts. Inspired by knowledge distillation methods, we propose a novel prompt compression methodology called P-Distill. This approach aims to compress the prompts while maintaining the performance, thereby increasing the available space for input tokens and enhancing the overall model efficiency. To this end, the proposed P-Distill comprises the following two methods: prompt initialization and prompt distillation. Figure 2 shows the learning and compression processes of P-Distill. Our approach involves two main steps where the first step is training a teacher model using P-tuning v2, and the second step focuses on distilling knowledge to a student model with shorter prompts, effectively reducing the length of the prompts.

3.1 Prompt-Based Teacher Learning

When solving downstream tasks using P-tuning v2, we freeze the pre-trained weights of the language model and only train the continuous prompts. Prompt lengths that yield good performance vary according to task complexity. In general, simple classification tasks tend to use shorter prompts,

around 20, while more complex sequence labeling tasks often require longer prompts, around 100 (Liu et al., 2022). Understanding the variation in prompt length is crucial, particularly during the inference stage, as longer prompts inherently limit the maximum sequence length that the model can handle.

We train a teacher model on various tasks based on the P-tuning v2 methodology. This model tokenizes input data x and embeds it into text embeddings $\overline{x}$. Subsequently, the continuous prompts P_k^T, $P_v^T \in R^{n_t \times d}$ of the teacher model are randomly initialized and concatenated with the key vectors $K \in R^{n_x \times d}$ and value vectors $V \in R^{n_x \times d}$ of each layer. Here, d is the dimensionality of the hidden representations, n_t is the prompt length of the teacher model, and n_x is the length of token embeddings. The teacher model, which utilizes attention heads incorporating continuous prompts, is trained to take the text embedding $\overline{x}$ as input and generate the final logits y^T. The parameter optimization of the teacher model is guided by the cross-entropy loss, which is formalized as follows:

$$L_{CE}^T = -\frac{1}{|B|}\sum_{i=1}^{|B|}\log(softmax(y_i^T)[c_i]), \quad (4)$$

where $|B|$ is the number of data points in the current batch, y_i^T is the logits output by the teacher model for the i-th data point in the batch, $softmax(y_i^T)$ is the softmax-transformed probability distribution over the classes, and c_i is the true class index for the i-th data point.

3.2 Prompt-enhanced Distillation (P-Distill)

We initiate the training of a student model which employs shorter continuous prompts, rather than the teacher model, using the same prompt attachment methodology. During the initial training phase, we initialize the continuous prompts of the student model P_k^S and $P_v^S \in R^{n_s \times d}$ based on the teacher model's prompts P_k^T and P_v^T. Subsequently, student prompts are also attached to the key and value vectors across all layers to compute the attention heads. The length of the student model prompts, represented by n_s, is shorter than that of the teacher model prompts n_t. The student model, denoted by f^S, takes the text embedding $\overline{x}$ as input and generates the output logits y^S. The teacher and student models share the same underlying language model architecture, differing only in the length and content of their respective prompts. In this context,

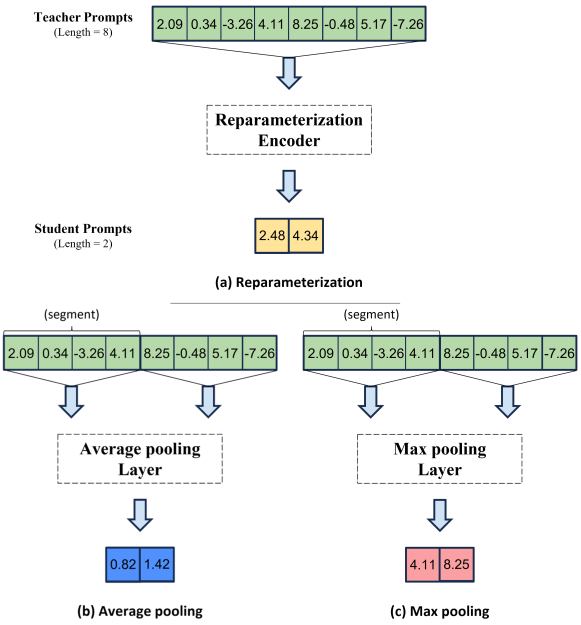


Figure 3: Illustration of various prompt initialization methods.

we focus on distilling the knowledge from the more extensive teacher model prompts into the shorter student model prompts. To enhance the effectiveness of knowledge transfer, we propose two novel methods for knowledge distillation.

3.2.1 Prompt Initialization

For solving downstream tasks, the model utilizes the attached prompts to generate answers. Starting with the randomly initialized prompts for the model can result in an unstable training process (Lester et al., 2021). To mitigate this challenge, the study (Vu et al., 2022) employed a method for transferring the prompts learned in one task to another task. We aim to stabilize the training by initializing the student model prompts P_k^S and P_v^S based on the teacher model prompts P_k^T, P_v^T. We experiment with various prompt initialization methods, including reparameterization, average pooling, and max pooling, as illustrated in Figure 3. In reparameterization, we employ a reparameterization encoder to adjust the length of the teacher model prompts to that of the student model prompts. For average pooling, we divide the teacher model's prompts into smaller segments and compute their averages to initialize the student prompts. In max pooling, we focus on the most prominent features by obtaining the maximum value from each segment of the teacher model's prompts. Based on the experimental results, we apply the reparameterization encoder to the teacher model's prompts to construct the stu-

dent model's prompts as follows:

$$P_k^S = (P_k^T \cdot W_k^T) + b_k^T, \quad (5)$$

$$P_v^S = (P_v^T \cdot W_v^T) + b_v^T, \quad (6)$$

where W_k^T and W_v^T are the learnable weight matrices used to construct the student's prompts, and b_k^T and b_v^T are the corresponding bias. The results of various prompt initialization experiments are shown in Section 4.5.

3.2.2 Prompt Distillation

In this section, we focus on prompt distillation, a key aspect of the proposed approach. Recognizing the influence of continuous prompts on both the hidden states and the prediction layer outputs within the model, we employ the following two distillation techniques: prediction layer and hidden state distillations. These techniques focus on different aspects of the teacher model's output to ensure comprehensive knowledge transfer.

Prediction layer distillation In this method, a student model learns to emulate the predictions of a teacher model. This process involves the student model utilizing soft labels from the teacher model's output, which encapsulate the teacher model's understanding of the data. Particularly, a loss function is used to minimize the difference between the logits y^S and y^T produced by the student and teacher models, respectively. The distillation loss L_{pred} is formulated as follows:

$$L_{pred} = KL(softmax(y_i^S/\theta), softmax(y_i^T/\theta)), \quad (7)$$

where y_i^S and y_i^T are the logits vectors predicted by the student and teacher, respectively, and KL denotes the Kullback-Leibler divergence, which measures the difference between the probability distributions of the two models. θ is a temperature hyperparameter that adjusts the smoothness of these distributions, enabling a more nuanced transfer of knowledge from the teacher to student model. The distillation loss L_{pred} is then used in the optimization process to update the parameters of the student model, thereby aligning its predictive behavior more closely with that of the teacher model.

Hidden state distillation Additionally, we also distill knowledge from the intermediate representations of the teacher model. The concept of distilling knowledge through intermediate representations was initially introduced by Fitnets (Romero et al., 2015), with the aim of enhancing the training process of the student model. Based on the provided prompts and inputs, we extract knowledge from the transformer layers of the teacher model and distill into the student model. This process is formalized using the loss function L_{hidden}, which is calculated as the MSE between the hidden states H_S and H_T of the student and teacher models, respectively, as follows:

$$L_{hidden} = MSE(H_S, H_T), \quad (8)$$

where the matrices $H_S, H_T \in R^{n \times d}$ represent the hidden states, n is the input sequence length, and d is the hidden state dimensionality of the two models.

3.3 Distillation-based Student Learning

While training the student model, the cross-entropy loss is computed similar as that of the teacher model. This loss serves as a measure of the student model's accuracy in predicting the true class labels as follows:

$$L_{CE}^S = -\frac{1}{|B|}\sum_{i=1}^{|B|} \log(softmax(y_i^S)[c_i]). \quad (9)$$

Subsequently, the overall loss function L_{total} for the student model is then a weighted combination of the cross-entropy loss and the distillation losses as follows:

$$L_{total} = \lambda_1 \cdot L_{CE}^S + \lambda_2 \cdot L_{pred} + \lambda_3 \cdot L_{hidden}, \quad (10)$$

where λ_1, λ_2, and λ_3 are the learnable weighted coefficients with the constraint that their combined sum equals 1. During the training, the teacher model parameters are fixed to serve as the sources of prior knowledge.

4 Experiments

This section presents the datasets employed in our experiments, baseline models for comparison, results of these datasets, and analyses from our additional studies.

4.1 Datasets

Our evaluation of the proposed P-Distill method includes a comprehensive range of natural language understanding tasks, utilizing datasets that are well-established benchmarks in the field.

	BoolQ Acc.	CB Acc.	COPA Acc.	MultiRC F1a	ReCoRD F1	RTE Acc.	WiC Acc.	WSC Acc.	Average
Fine-tuning	**0.777**	0.946	0.710	0.705	0.706	0.762	0.746	0.683	0.754
P-tuning v2	$0.764_{(8)}$	$0.946_{(32)}$	$\mathbf{0.810}_{(4)}$	$0.711_{(16)}$	$\mathbf{0.728}_{(16)}$	$0.794_{(4)}$	$0.756_{(4)}$	$\mathbf{0.731}_{(16)}$	0.780
	$0.738_{(1)}$	$0.929_{(4)}$	$0.790_{(1)}$	$0.707_{(2)}$	$0.721_{(2)}$	$0.783_{(1)}$	$0.745_{(1)}$	$0.692_{(2)}$	0.763
P-Distill	$0.776_{(1)}$	$\mathbf{0.964}_{(4)}$	$\mathbf{0.810}_{(1)}$	$\mathbf{0.718}_{(2)}$	$0.726_{(2)}$	$\mathbf{0.798}_{(1)}$	$\mathbf{0.759}_{(1)}$	$0.721_{(2)}$	**0.784**

Table 1: Experimental results on the SuperGLUE validation dataset. For P-Distill, training was performed using a teacher model with the prompt length exhibiting the best performance for P-tuning v2. The numbers in parentheses indicate the lengths of the prompt attached to the model. (Acc.: Accuracy; **bold**: the best; underline: the second best)

We include various tasks from the SuperGLUE benchmark (Wang et al., 2019), which assesses a model's understanding and reasoning abilities across different contexts, including BoolQ (Clark et al., 2019), CB (De Marneffe et al., 2019), COPA (Roemmele et al., 2011), MultiRC (Khashabi et al., 2018), ReCoRD (Zhang et al., 2018), RTE (Dagan et al., 2006; Bar Haim et al., 2006), WiC (Pilehvar and Camacho-Collados, 2019) and WSC (Levesque et al., 2011). We also utilize the CoNLL-2003 (Tjong Kim Sang and De Meulder, 2003), CoNLL-2004 (Carreras and Màrquez, 2004), CoNLL-2005 (Carreras and Màrquez, 2005), CoNLL-2012 (Pradhan et al., 2012), and OntoNotes 5.0 datasets (Weischedel et al., 2013), each providing richly annotated text for entity classification. The SQuAD dataset, in its versions 1.1 (Rajpurkar et al., 2016) and 2.0 (Rajpurkar et al., 2018), facilitates testing reading comprehension, requiring the model to parse passages and answer questions with a high degree of understanding. In addition, we extend our experiments to the Allsides dataset (Li and Goldwasser, 2019), which consists of news articles with an average token length of over 1000. This dataset allows us to examine the effects of P-Distill in scenarios where input tokens are frequently truncated. All of these datasets are English, open source, and used for academic research purposes only. For accurate comparisons, we follow the train, validation, and test set splits as specified in the referenced work (Liu et al., 2022).

4.2 Baselines

We compare P-Distill against the following methods to validate its competitive performance, with all methods utilizing BERT$_{large}$ with 335M parameters as the backbone architecture.

Fine-tuning All parameters of a PLM are updated and adapted to the given downstream task in a task-specific manner.

P-tuning v2 (Liu et al., 2022) It appends trainable continuous prompts to the key and value matrices of a model, enabling task-specific learning while keeping the model's pre-trained weights fixed.

4.3 Experimental Details

In our training process, we exclusively focus on continuous prompts while keeping the backbone parameters of the model fixed. The model is trained with a batch size of 16, and the learning rate is individually optimized for each task. Furthermore, we employ the AdamW optimizer for training. For the temperature hyperparameter θ used in the distillation process, we experimentally determine the optimal setting by sweeping across {1, 5, 10}. For the learnable parameter λ_2, we explore the initial values of {0.1, 0.5, 0.9}. Considering the significant impact of the hidden state loss, we experiment with the initial values of {1e-3, 1e-4, 1e-5} for λ_3. All experiments were performed using PyTorch [1] and HuggingFace Transformers (Wolf et al., 2020) on three NVIDIA A100 GPUs, and to ensure consistency in our results, each task was conducted using a fixed random seed.

4.4 Results

Tables 1 and 2 present the experimental results of Fine-tuning, P-tuning v2, and P-Distill. In P-Distill, the prompt length is compressed to one-eighth of that of the teacher model prompts. For fewer than eight teacher model prompts, the length is compressed to 1. For a detailed analysis of prompt compression ratios refer to Appendix A. In general, the proposed P-Distill method exhibits a comparable or superior performance than those of the other methods while using shorter prompts.

Results on SuperGLUE Table 1 shows the performance of each approach on the SuperGLUE benchmark. The experimental results show that

[1] https://pytorch.org/

	NER			SRL		QA		SC
	CoNLL03	CoNLL04	OntoNotes 5.0	CoNLL05 Brown	CoNLL05 WSJ	SQuAD 1.1 dev	SQuAD 2.0 dev	Allsides
Fine-tuning	**0.928**	0.882	**0.890**	0.827	0.885	**0.911**	**0.819**	0.780
P-tuning v2	0.919$_{(64)}$ 0.914$_{(8)}$	0.880$_{(128)}$ 0.866$_{(16)}$	0.885$_{(128)}$ 0.881$_{(16)}$	**0.837**$_{(32)}$ 0.807$_{(4)}$	**0.890**$_{(128)}$ 0.877$_{(16)}$	0.902$_{(64)}$ 0.891$_{(8)}$	0.782$_{(128)}$ 0.771$_{(16)}$	0.775$_{(32)}$ 0.772$_{(4)}$
P-Distill	0.919$_{(8)}$	**0.888**$_{(16)}$	0.886$_{(16)}$	0.817$_{(4)}$	0.885$_{(16)}$	0.896$_{(8)}$	0.775$_{(16)}$	**0.783**$_{(4)}$

Table 2: Experimental results for each method on named entity recognition (NER), question answering (QA), semantic role labeling (SRL), and long sequence classification (SC). For P-Distill, training was performed using a teacher model with the prompt length exhibiting the best performance for P-tuning v2. The numbers in parentheses indicate the lengths of the prompts attached to the model. All metrics are reported as f1 scores. (**bold**: the best; underline: the second best)

despite using shorter prompts, P-Distill matches or exceeds the performance of P-tuning v2 which utilizes long prompts. Specifically, P-Distill exhibits 0.51% performance improvement on average on SuperGLUE tasks. The improvement increases to 2.75% when compared to P-tuning v2 with the same prompt length. These results reveal that P-Distill effectively compresses the prompt length while maintaining or even improving performance. This highlights the significance of the proposed distillation method that transfers task knowledge from the teacher to the student model using eight times shorter prompts.

Results on Other Tasks Table 2 presents the experimental results for diverse tasks, including named entity recognition, question answering, semantic role labeling, and long sequence classification. We first observe that achieving superior performance via P-tuning v2 on these tasks requires training with longer prompts (up to 128 tokens), which aligns with the phenomenon reported in previous work (Liu et al., 2022) where complex tasks tend to require long prompts.

In comparison to the baseline methods, P-Distill achieves comparable performance using significantly shorter prompts even for tasks where P-tuning v2 employs long prompts. In particular, P-Distill outperforms P-tuning v2 with 128 prompt tokens on CoNLL04 while utilizing a prompt of length 16. Furthermore, P-Distill achieves a performance improvement of 2.54% over the prompt of the same length trained using P-tuning v2, and a 0.90% improvement over the teacher model.

Moreover, P-Distill outperforms the baseline methods on the Allsides dataset, which consists of long input instances where the average token length exceeds 1000. Specifically, with prompts significantly compressed to 4, P-Distill not only mitigates token truncation issues but also shows a 1.03% performance improvement over the best P-tuning v2 configuration. This highlights the advantage of P-Distill in handling long-sequence tasks by preserving input space with shorter prompts. Additionally, P-Distill exhibits 1.42% performance improvement when compared to P-tuning v2 with prompt length 4, showing that P-Distill is an effective method for compressing prompt length. A qualitative evaluation of the Allsides dataset is provided in Appendix D, offering further insights on long-sequence tasks.

4.5 Ablation Study

To further verify the effectiveness of the proposed method, we conduct ablation studies using the following variants of P-Distill.

P-Distill$_{-init}$ Instead of training with prompt initialization, it focuses exclusively on leveraging the two types of distillation losses designed to transfer the knowledge from the teacher to student model in different ways.

P-Distill$_{-pred}$ This approach does not implement the prediction layer distillation loss. Following the application of the prompt initialization method, it trains the student model based on the hidden state distillation loss. This method aligns the internal representations of the student model with those of the teacher model without focusing on the final output predictions.

P-Distill$_{-hidden}$ This variant does not consider the differences between the hidden state outputs of the teacher and student models. Instead, it focuses on training based on the differences in the prediction layer output. This approach aligns the final predictions of the student model closely with those of the teacher model without directly focusing on their internal representations.

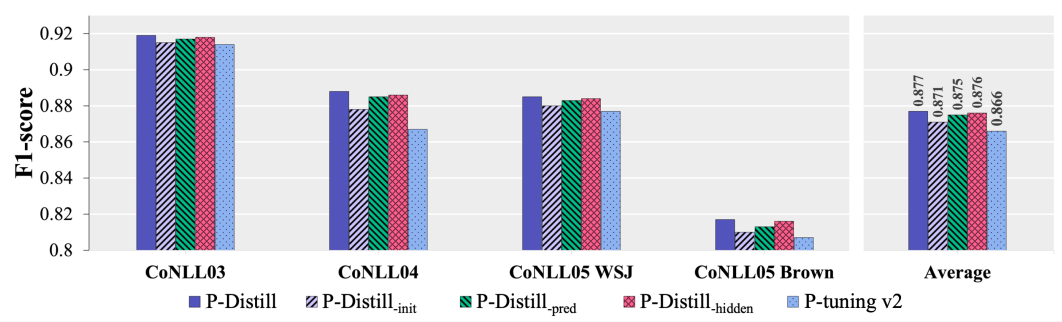


Figure 4: Comparison of ablation study results across various tasks, with different colors and bar styles representing the distinct variants of P-Distill.

Results Figure 4 shows that all three variants of P-Distill underperform the original P-Distill among various tasks. This shows that each component of P-Distill contributes to the performance achieved on downstream tasks.

Given these results, we further observe that the extent of degradation varies among different variants. First, P-Distill$_{-init}$ exhibits the most significant performance degradation across various tasks. While not utilizing prompt initialization and only conducting prediction layer distillation and hidden state distillation still led to performance improvements over P-tuning v2, the degradation in performance is clear compared to other variants and the original P-Distill. This indicates that prompt initialization, based on the teacher model's prompt, is crucial in prompt-based knowledge distillation. Second, P-Distill$_{-hidden}$ and P-Distill$_{-pred}$ exhibited decreased prediction performance. This demonstrates that integrating prompt initialization with the hidden state or prediction layer distillation techniques enhances the stability and effectiveness of knowledge distillation.

4.6 Impact of Prompt Initialization

To inspect the impact of different prompt initialization methods within P-Distill, we conduct experiments to compare the performance of P-Distill with two variants: P-Distill$_{mean}$, which initializes the student model prompts using an average pooling layer over the teacher model prompts, and P-Distill$_{max}$, which uses a max pooling layer for the same purpose.

The results, as detailed in Table 3, demonstrate that both P-Distill$_{mean}$ and P-Distill$_{max}$ underperform P-Distill which utilizes a reparameterization encoder for prompt initialization. We conjecture that the use of average pooling and max pooling leads to an excessive simplification of the teacher model's prompts, resulting in the loss of crucial nuances and complexities. Conversely, the reparameterization encoder for prompt initialization effectively captures and transfers the complex knowledge of the teacher model prompts without loss of crucial task information. This suggests that the reparameterization encoder is a more suitable method for prompt initialization in P-Distill, contributing significantly to the overall effectiveness of the knowledge distillation process.

	CoNLL03	CoNLL04	CoNLL05 WSJ	CoNLL05 Brown
P-Distill	**0.919**	**0.888**	**0.885**	**0.817**
P-Distill$_{mean}$	0.915	0.875	0.878	0.809
P-Distill$_{max}$	0.912	0.872	0.872	0.803

Table 3: Comparison of additional experiment results across various tasks based on prompt initialization methods. All metrics are reported as micro-f1 scores. (**bold**: the best)

5 Conclusion

In this paper, we introduce P-Distill, a novel approach in NLP that utilizes two knowledge distillation techniques to enhance performance by compressing unnecessary prompt length. This approach combines prompt initialization, two types of prompt distillation to effectively transfer knowledge from a teacher model with longer prompts to a student model with prompts that are eight times shorter. To evaluate the efficacy of our proposed method, we conduct experiments across various NLP tasks. Our results demonstrate that using prompts of the same length, the proposed method achieves an average improvement of 2.75% over the existing prompt-tuning methods across the SuperGLUE benchmark. Furthermore, P-Distill exhibits competitive performance even against models trained with prompts that are eight times longer.

Limitations

One limitation of this study is that we evaluated our method only on the BERT architecture. Conducting additional experiments on other architectures could be beneficial to determine the generalizability of our findings. Additionally, while our model improves performance through the process of training a teacher model and transferring its knowledge, it incurs more time and cost compared to previous methods. In future work, we plan to develop an approach that integrates the training of the teacher model and the knowledge distillation process in an end-to-end manner.

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Appendix

A Impact of Compression Ratio

	CoNLL05 WSJ
Fine-tuning	0.885
P-tuning v2	**0.890**$_{(128)}$
P-Distill	**0.890**$_{(64)}$
	0.888$_{(32)}$
	0.885$_{(16)}$

Table 4: Comparison of P-Distill performance across varying prompt compression ratios.

To investigate the impact of different compression ratios on the performance of P-Distill, we conduct additional experiments with 2× and 4× compression ratios and compare the results. We use CoNLL04 dataset in these experiments, as it is known to require longer prompts for sufficient training.

Table 4 presents the performance results for these different compression ratios within CoNLL04. We observe a trade-off between compression ratio and model performance, as a higher compression ratio leads to relatively lower performance. Yet, it is worth noting that a 2× compression with P-Distill does preserve the performance of the original long prompt, and that P-Distill still matches the performance of fine-tuning at the compression ratio of 8×.

B Experimental Results of Applying P-Distill to P-tuning Methodology

	CB	COPA	RTE
Fine-tuning	0.946	0.71	0.762
P-tuning	0.821$_{(16)}$	0.76$_{(16)}$	0.657$_{(16)}$
	0.786$_{(2)}$	0.70$_{(2)}$	0.621$_{(4)}$
P-Distill	0.821$_{(2)}$	0.76$_{(2)}$	0.646$_{(4)}$

Table 5: Experimental results on the SuperGLUE validation dataset for small datasets (CB, COPA, RTE). For P-Distill, training was performed using a teacher model with the prompt length exhibiting the best performance for P-tuning. The numbers in parentheses indicate the lengths of the prompt attached to the model. All metrics are accuracy.

To evaluate the effectiveness of P-Distill when the prompts directly occupy the input sequence space, we apply P-Distill to the P-tuning methodology that attaches prompts to the input embeddings. The experimental results are shown in Table 5.

These results demonstrate the effectiveness of applying P-Distill to the P-tuning methodology. When P-Distill is used, it shows higher performance across all datasets compared to using prompts of the same length without P-Distill. Particularly, on the CB and COPA datasets, P-Distill achieves the same performance as the teacher prompts despite compressing the prompts to one-eighth. These results indicate that P-Distill effectively compresses the prompt length while maintaining performance, even when the prompts are attached to the input embeddings.

C Inference Costs

	Fine-tuning	P-tuning v2	P-Distill
BoolQ	89.06	89.17$_{(8)}$	89.07$_{(1)}$
CB	53.94	54.22$_{(32)}$	53.97$_{(4)}$
COPA	21.82	21.83$_{(4)}$	21.82$_{(1)}$
MultiRC	226.94	227.50$_{(16)}$	227.01$_{(2)}$
ReCoRD	163.12	163.53$_{(16)}$	163.17$_{(2)}$
RTE	42.78	42.81$_{(4)}$	42.79$_{(1)}$
WiC	18.83	18.84$_{(4)}$	18.83$_{(1)}$
WSC	23.11	23.17$_{(4)}$	23.11$_{(1)}$

Table 6: Comparing GFLOPs of baseline methods and P-Distill on SuperGLUE using BERT$_{large}$.

To examine the benefits of P-Distill at the inference stage, we compare the inference costs across P-Distill, Fine-tuning, and P-tuning v2. This reduction in computational requirements is quantified in Table 6, which presents the GFLOPs required during the inference stage with average length samples from each task in the SuperGLUE benchmark.

While both P-tuning v2 and P-Distill demonstrate increased inference GFLOPs compared to fine-tuning due to the inclusion of prompts, we observe that P-Distill adds fewer computations compared to P-tuning v2. The difference is more clear in cases where long prompts are utilized in P-tuning v2. This demonstrates the advantage of compressing prompt length in terms of lowering computational costs.

D Qualitative Analysis in Long Sequence Classification

To further examine the effectiveness of expanding the input space by using shorter prompts via P-

P-tuning v2 Input Text (480 tokens): President Trump on Wednesday lashed out over a critical news report and escalated his previous attacks on the media by suggesting that news organizations he disagrees with be shut down, alarming free-speech advocates who compared the tactics to intimidation efforts by the Nixon administration. [...] Last week, angered by the ongoing investigations into his campaign's ties to Russia, Trump suggested that the Senate Intelligence Committee investigate news outlets over "fake news." Over the weekend, he expressed disdain at late-night television hosts over their "anti-Trump" material and *proposed bringing back the Fairness Doctrine, a rule phased out in 1987 that had required* **Prediction**: Left
P-Distill Input Text (508 tokens): President Trump on Wednesday lashed out over a critical news report and escalated his previous attacks on the media by suggesting that news organizations he disagrees with be shut down, alarming free-speech advocates who compared the tactics to intimidation efforts by the Nixon administration. [...] Last week, angered by the ongoing investigations into his campaign's ties to Russia, Trump suggested that the Senate Intelligence Committee investigate news outlets over "fake news." Over the weekend, he expressed disdain at late-night television hosts over their "anti-Trump" material and *proposed bringing back the Fairness Doctrine, a rule phased out in 1987 that had required broadcasters to provide "equal time" for divergent political views on certain issues.* First Amendment advocates roundly condemned the president over his remarks, calling them an assault **Prediction**: Center

Table 7: Example of P-tuning v2 and P-Distill Predictions in the Allsides Dataset.

Distill, we conduct a qualitative analysis on the Allsides dataset. The task of it is to predict the political perspectives inherent in a news article. Therefore, the dataset consists of news articles that generally exceed the model's input capacity of 512 tokens.

We compare the input text and prediction results of P-tuning v2, trained with 32 prompt tokens, to those of P-Distill, which compresses and appends only 4 prompt tokens, which are shown in Table 7. Note that while P-tuning v2 can utilize up to 480 input tokens by attaching 32 prompt tokens, P-Distill extends the input capacity by using up to 508 input tokens with only 4 prompt tokens appended.

We observe that the P-tuning v2 model cannot access the detailed explanation of the Fairness Doctrine due to its limited input space. However, P-Distill can access the remainder of the sentence, namely '*broadcasters provide "equal time" to divergent political views.*', which provides the key information for the model in making an accurate prediction 'Center'. This example verifies that the input space preserved by compressing the prompt length with P-Distill can contribute to accurate prediction of the model, leading to better performance overall.