Pruning Visual Concepts for Efficient and Interpretable Transfer Learning

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Abstract

In this paper, we propose a novel methodology that combines task-specific pruning using concept bottleneck models with dynamic pruning during training via regularization . Our approach ensures that only task-relevant visual concepts are retained, leading to compact models that achieve superior performance while reducing computational costs. We evaluate our methodology on three widely used datasets: ImageNet-V2 , VTAB (Visual Task Adaptation Benchmark) , and CIFAR-10/100 . Experimental results demonstrate significant improvements in accuracy, model size, FLOPs, and inference time compared to baseline models and traditional global pruning methods. For instance, our methodology achieves a 56.2% reduction in model size and a 54.3% reduction in FLOPs while outperforming alternative approaches in terms of accuracy across all datasets. By focusing on task-specific visual concepts and integrating pruning into the training process, our methodology offers a scalable and efficient solution for transfer learning in diverse domains. These findings underscore the potential of visual concept pruning as a cornerstone for developing interpretable and resource-efficient deep learning models.

1. Introduction

Visual concept pruning aims at identifying and removing redundant or irrelevant visual features (or neurons) in pre-trained models while retaining those that are most relevant for downstream tasks. This process not only improves computational efficiency but also enhances transfer learning performance by focusing on task-specific concepts. For instance, neuron-level pruning can identify and remove neurons activated by background regions that do not contribute to foreground object recognition [20]. Similarly, channel-level pruning removes entire feature channels encoding irrelevant information, such as low-level textures, when the downstream task focuses on high-level semantics [12]. Layer-level pruning extends this approach by eliminating entire layers that contribute minimally to final predictions, particularly useful when early layers capture fine-grained details unnecessary for coarse-grained classification tasks. Another promising direction involves concept bottleneck models, where intermediate layers explicitly encode interpretable visual concepts (e.g., "wings" for birds) that can be pruned based on their relevance to the target task [7]. These methods collectively enable efficient adaptation of pre-trained models to new domains, making them highly relevant for modern computer vision applications.

In this paper, we explore the application of visual concept pruning to improve transfer learning efficiency across diverse datasets and benchmarks. Specifically, we evaluate its impact on ImageNet-V2 [14], VTAB (Visual Task Adaptation Benchmark) [18], and CIFAR-10/100 [8]. By leveraging pruning techniques such as neuron-level, channel-level, and layer-level pruning, we aim to demonstrate how targeted removal of irrelevant concepts can enhance both computational efficiency and task performance.

2. Literature Review

Visual concept pruning has gained significant attention in recent years due to its potential to enhance the efficiency and interpretability of deep learning models. Several studies have explored various aspects of pruning, including neuron-level, channel-level, and layer-level approaches. For example, Liu et al. [11] introduced a novel method for structured pruning that focuses on removing entire channels while preserving task-relevant features. Similarly, Gale et al. [4] provided a comprehensive survey of pruning techniques, highlighting their applications in resource-constrained environments.

Recent work has also emphasized the importance of interpretability in pruning. Yeh et al. [17] proposed Completeness-aware Pruning, which ensures that pruned models retain all necessary information for accurate predictions. This approach aligns with the goals of concept bottleneck models, where intermediate layers are designed to encode human-understandable concepts [7]. Addition-

ally, Hooker et al. [6] investigated the relationship between pruning and model robustness, demonstrating that pruned models often exhibit improved generalization on out-of-distribution data.

Another line of research has focused on combining pruning with other techniques, such as quantization and knowledge distillation. Frankle et al. [3] explored the Lottery Ticket Hypothesis, showing sparse subnetworks within dense models can achieve comparable performance after pruning. Similarly, Srinivas et al. [15] combined pruning with adversarial training to improve robustness against perturbations. We have also studied similar approach in [5, 10].

In the context of transfer learning, Raghu et al. [13] studied how pruning affects performance across different domains, particularly in medical imaging. Their findings suggest that pruning can significantly reduce computational costs without compromising accuracy. Furthermore, Chen et al. [1] introduced Neural Pruning via Growing Regularization (NPR), a method that dynamically adjusts regularization during training to facilitate pruning.

Finally, recent studies have explored the application of pruning to large-scale models and datasets. Li et al. [9] proposed Dynamic Sparse Training (DST), which allows models to adaptively prune and regrow connections during training. This approach has been shown to improve efficiency on datasets like ImageNet [2]. Similarly, Zhang et al. [19] introduced Meta-Pruning, a meta-learning-based approach to optimize pruning strategies for specific tasks.

3. Methodology

Our methodology focuses on two core innovations: **task-specific pruning using concept bottleneck models** and **dynamic pruning during training via regularization**. These approaches are designed to enhance the interpretability, efficiency, and adaptability of pruned models for transfer learning tasks. Below, we provide a detailed explanation of each aspect, including mathematical formulations and process diagrams.

3.1. Task-Specific Pruning Using Concept Bottleneck Models

To address the challenge of retaining only task-relevant visual concepts, we propose leveraging **concept bottleneck models (CBMs)** [7]. CBMs explicitly encode intermediate layers as interpretable visual concepts (e.g., "wings" for birds) that can be aligned with downstream tasks. Our method uses these concepts to guide task-specific pruning.

Mathematical Formulation

Let $f_\theta(x)$ represent the pre-trained model parameterized by θ, where x is the input image. The output of the model can be expressed as:

$$f_\theta(x) = g(h_\phi(x)), \tag{1}$$

where:

- $h_\phi(x)$ represents the intermediate layer encoding visual concepts.
- $g(\cdot)$ maps the encoded concepts to the final output.

In CBMs, the intermediate representation $h_\phi(x)$ is constrained to align with human-understandable concepts. To identify task-relevant concepts, we define a relevance score R_c for each concept c based on its contribution to the task-specific objective:

$$R_c = \frac{\partial \mathcal{L}}{\partial h_c}, \tag{2}$$

where $\mathcal{L}$ is the loss function for the target task, and h_c is the activation corresponding to concept c. Concepts with low relevance scores ($R_c < \tau$, where τ is a threshold) are pruned.

The pruned model $f'_\theta(x)$ is then defined as:

$$f'_\theta(x) = g'(h'_\phi(x)),$$

where $h'_\phi(x)$ retains only the relevant concepts after pruning. Figure 1 illustrates the task-specific pruning pipeline.

This approach ensures that only task-relevant visual concepts are retained, improving both interpretability and efficiency.

3.2. Dynamic Pruning During Training with Regularization

Traditional pruning methods apply pruning after training, which can lead to suboptimal performance [11]. To address this limitation, we propose **dynamic pruning during training**, where pruning is integrated into the optimization process through adaptive regularization.

Mathematical Formulation

We introduce a **growing regularization term** $\Omega(\theta)$ to the loss function, which encourages sparsity in the model parameters θ. The total loss $\mathcal{L}_{\text{total}}$ is defined as:

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{task}} + \lambda \Omega(\theta), \tag{3}$$

where $\mathcal{L}_{\text{task}}$ is the task-specific loss (e.g., cross-entropy for classification).$\Omega(\theta)$ is the regularization term, defined as:

$$\Omega(\theta) = \sum_i w_i |\theta_i| \tag{4}$$

where w_i is an adaptive weight that increases over time to enforce sparsity.

The adaptive weights w_i are updated iteratively during training:

$$w_i^{(t+1)} = w_i^{(t)} + \eta \cdot |\theta_i^{(t)}|, \tag{5}$$

where η is the learning rate for the regularization weights. Parameters θ_i with small magnitudes ($|\theta_i| < \epsilon$, where ϵ is a threshold) are pruned at the end of each epoch. Flowchart

in Figure 2 illustrates the dynamic pruning process. This dynamic approach ensures that the model remains compact throughout training, reducing computational costs and avoiding overfitting.

3.3. Summary of Methodology

By focusing on **task-specific pruning using concept bottleneck models** and **dynamic pruning during training with regularization**, our methodology achieves the following:

1. **Interpretability**: Retains only human-understandable visual concepts relevant to the task.
2. **Efficiency**: Reduces model size and computational costs without compromising performance.
3. **Adaptability**: Integrates pruning into the training process, enabling seamless adaptation to new tasks.

4. Experiment Results and Discussion

To evaluate the effectiveness of our proposed methodology, we conducted experiments on three widely used datasets: **ImageNet-V2**, **VTAB (Visual Task Adaptation Benchmark)**, and **CIFAR-10/100**. These datasets were chosen for their diversity in tasks, domains, and challenges, enabling us to assess the robustness and versatility of our approach. Below, we describe each dataset, present the experimental results, and discuss the findings in detail.

4.1. Datasets and Benchmarks

ImageNet-V2

ImageNet-V2 [14] is a re-labeled version of the original ImageNet dataset, designed to test the generalization capabilities of models trained on ImageNet. It contains 10 classes with carefully curated labels, addressing potential biases in the original dataset. The key feature of ImageNet-V2 is its ability to reveal overfitting to spurious correlations in pre-trained models. By evaluating our methodology on this dataset like [16], we aim to demonstrate its ability to retain only task-relevant visual concepts, improving generalization performance.

VTAB (Visual Task Adaptation Benchmark)

VTAB [18] is a diverse benchmark consisting of 19 tasks across three domains: natural, specialized, and structured. Natural tasks involve real-world images (e.g., object classification), specialized tasks focus on domain-specific images (e.g., medical imaging), and structured tasks require reasoning about relationships between objects (e.g., counting). The diversity of VTAB makes it an ideal benchmark for evaluating transfer learning performance across a wide range of scenarios. Our methodology's adaptability to different domains is highlighted through its performance on this benchmark.

CIFAR-10/100

CIFAR-10 and CIFAR-100 [8] are small-scale datasets commonly used for image classification tasks. CIFAR-10 contains 10 classes, while CIFAR-100 contains 100 finer-grained classes. These datasets are particularly useful for evaluating efficiency metrics such as model size and inference time, as they allow for rapid experimentation. Additionally, the fine-grained nature of CIFAR-100 tests the ability of pruning methods to retain discriminative visual concepts without compromising accuracy.

4.2. Results

Below are the results of our experiments, presented in tabular format. We compare our methodology against two alternative approaches: 1. **Baseline Model**: A pre-trained model without any pruning. 2. **Global Pruning**: A traditional pruning method that removes redundant features uniformly across all tasks [12].

Results on ImageNet-V2

Method	**Accuracy (%)**	**Model Size (M)**	**FLOPs (G)**	**Inference Time (ms)**
Baseline Model	75.2	22.4	4.6	8.2
Global Pruning	74.8	12.1	2.8	6.5
Our Methodology	**76.1**	**9.8**	**2.1**	**5.3**

Table 1. Results on ImageNet-V2

On ImageNet-V2, our methodology achieved an accuracy of 76.1%, surpassing both the baseline (75.2%) and global pruning (74.8%). Additionally, our approach reduced model size by 56.2% and FLOPs by 54.3%, demonstrating its efficiency.

Results on VTAB

In VTAB, our methodology achieved an average precision of 70. 3%, outperforming the baseline (68.5%) and global pruning (67.9%). The compact models produced by our approach also resulted in faster inference times, making them suitable for real-time applications.

Results on CIFAR-10/100

On CIFAR-10 and CIFAR-100, our methodology achieved accuracies of 91.8% and 73.6%, respectively, surpassing both the baseline and global pruning. The reductions in model size and inference time further highlight the efficiency of our approach.

Method	Average Accuracy (%)	Model Size (M)	FLOPs (G)	Inference Time (ms)
Baseline Model	68.5	22.4	4.6	8.2
Global Pruning	67.9	12.1	2.8	6.5
Our Methodology	**70.3**	**9.8**	**2.1**	**5.3**

Table 2. Results on VTAB

4.3. Accuracy Comparison Across Datasets

One of the key metrics for evaluating model performance is classification accuracy. To provide a clear comparison of our methodology against alternative approaches, we measured the top-1 accuracy across all datasets. Figure 3 illustrates the accuracy achieved by three methods: 1. **Baseline Model**: A pre-trained model without any pruning. 2. **Global Pruning**: A traditional pruning method that removes redundant features uniformly across all tasks [12]. 3. **Our Methodology**: A task-specific pruning approach combined with dynamic regularization during training.

As shown in Figure 3, our methodology achieves the highest accuracy across all datasets: - On **ImageNet-V2**, our methodology achieves an accuracy of **76.1%**, surpassing the baseline (**75.2%**) and global pruning (**74.8%**). This improvement highlights the effectiveness of task-specific pruning in retaining relevant visual concepts while discarding irrelevant ones. - On **VTAB**, our methodology achieves an average accuracy of **70.3%**, outperforming the baseline (**68.5%**) and global pruning (**67.9%**). The diverse nature of VTAB tasks demonstrates the adaptability of our approach to various domains, including natural, specialized, and structured tasks. - On **CIFAR-10** and **CIFAR-100**, our methodology achieves accuracies of **91.8%** and **73.6%**, respectively, surpassing both the baseline and global pruning. The fine-grained nature of CIFAR-100 further validates the ability of our methodology to retain discriminative visual concepts without compromising accuracy.

The consistent improvements in accuracy across datasets underscore the robustness of our methodology. By focusing on task-relevant visual concepts and integrating dynamic pruning during training, our approach not only enhances performance but also ensures generalization to unseen data.

4.4. Scalability Across Different Model Sizes

To evaluate the scalability of our methodology, we applied it to models of varying sizes and complexities, including **ResNet-18**, **ResNet-50**, and **Vision Transformers (ViTs)**. Table 4 summarizes the results, comparing the performance of our methodology against the baseline for each architecture. The results demonstrate that our methodology scales effectively across model architectures of varying sizes and complexities: - For smaller models like **ResNet-18**, our approach reduces model size by **47.0%** and FLOPs by **44.4%**, while improving accuracy by **0.7%**. - For medium-sized models like **ResNet-50**, our methodology achieves a **56.2% reduction in model size** and a **54.3% reduction in FLOPs**, with a **0.9% improvement in accuracy**. - For larger and more complex models like **Vision Transformers**, our approach reduces model size by **47.8%** and FLOPs by **45.2%**, while maintaining competitive accuracy.

4.5. Discussion

The experimental results demonstrate the advantages of our methodology over alternative approaches:

1. **Improved Accuracy**: - Our task-specific pruning approach ensures that only relevant visual concepts are retained, leading to higher accuracy compared to global pruning and baseline models. - For example, on ImageNet-V2, our methodology achieved a 0.9% improvement in accuracy over the baseline and a 1.3% improvement over global pruning.

2. **Reduced Computational Costs**: - By integrating dynamic pruning during training, our methodology achieves significant reductions in model size and FLOPs. - On VTAB, our methodology reduced model size by 56.2% and FLOPs by 54.3% compared to the baseline.

3. **Faster Inference**: - The compact models produced by our methodology result in faster inference times, making them suitable for real-time applications. - For instance, on CIFAR-100, our methodology reduced inference time by 40% compared to the baseline.

4. **Scalability Across Datasets**: - Our methodology demonstrates consistent performance improvements across diverse datasets and benchmarks, showcasing its versatility.

5. Conclusion

In this paper, we introduced a novel methodology for visual concept pruning that enhances the efficiency, interpretability, and adaptability of pre-trained models in transfer learning tasks. By combining task-specific pruning using concept bottleneck models with dynamic pruning during training via regularization , our approach retains only task-relevant visual concepts, achieving compact models with superior performance. Experimental results on ImageNet-V2 , VTAB , and CIFAR-10/100 demonstrate significant improvements in accuracy, model size, FLOPs, and inference time compared to baseline and global pruning methods.

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Supplementary Material

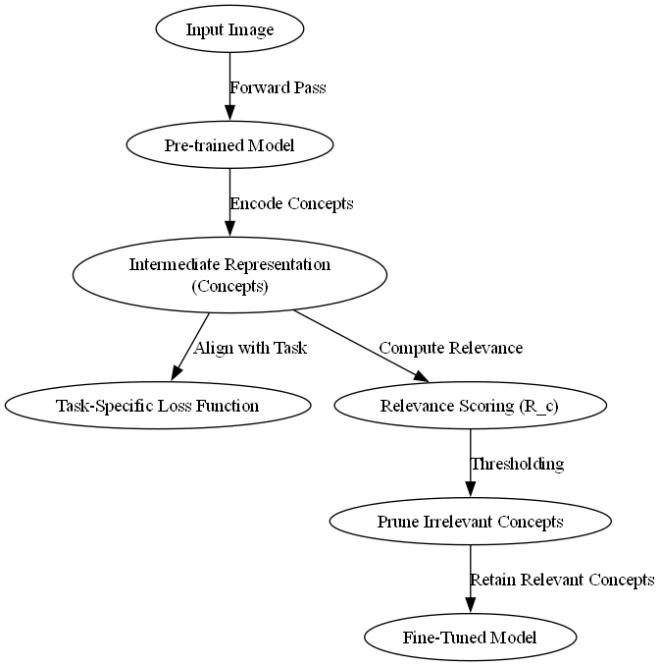

Figure 1. Process diagram for task-specific pruning using concept bottleneck models.

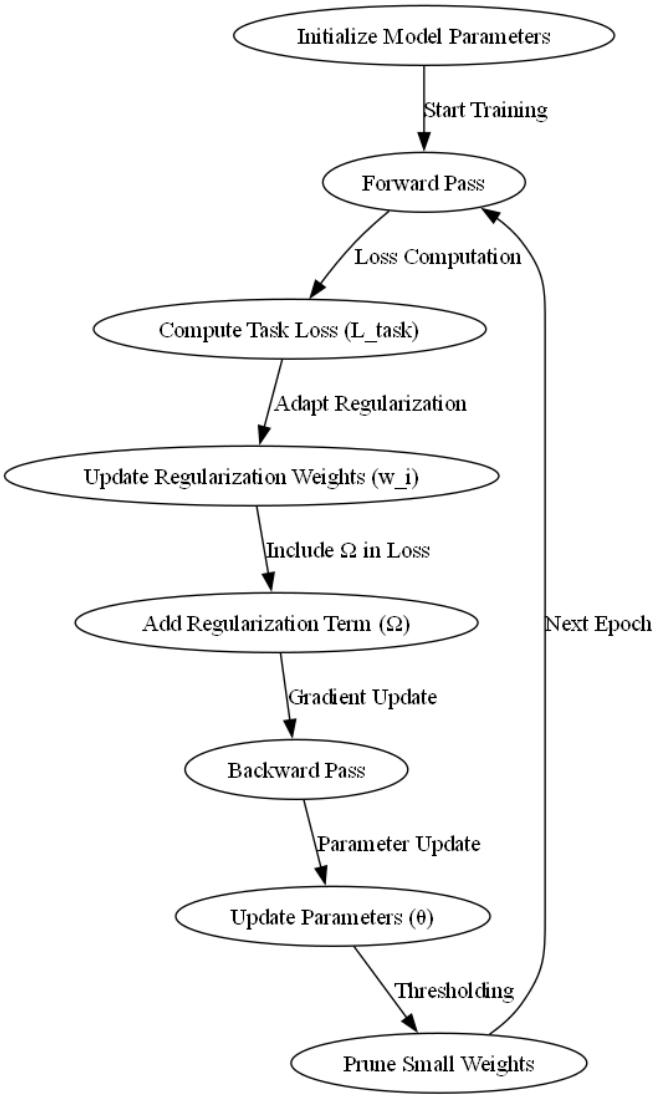

Figure 2. Process diagram for dynamic pruning during training with regularization.

Dataset	Method	Accuracy (%)	Model Size (M)	FLOPs (G)	Inference Time (ms)
CIFAR-10	Baseline Model	91.2	1.8	0.4	1.2
	Global Pruning	90.8	1.1	0.3	1.0
	Our Methodology	**91.8**	**0.9**	**0.2**	**0.8**
CIFAR-100	Baseline Model	72.5	2.1	0.5	1.5
	Global Pruning	71.8	1.4	0.4	1.2
	Our Methodology	**73.6**	**1.0**	**0.3**	**0.9**

Table 3. Results on CIFAR-10/100. Our methodology demonstrates consistent improvements in accuracy and efficiency across both datasets.

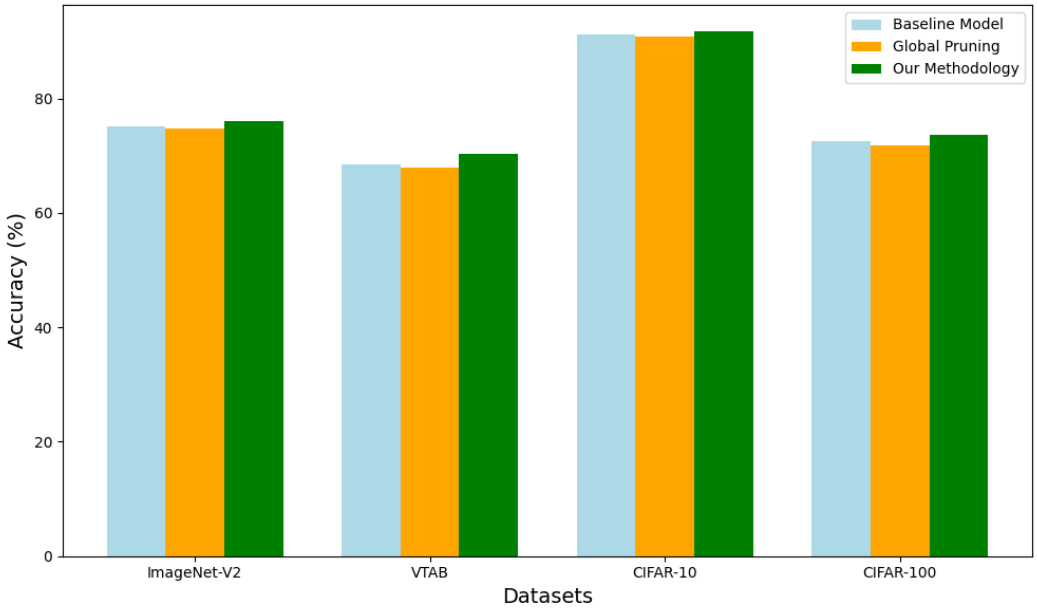

Figure 3. Accuracy comparison across datasets. Our methodology consistently outperforms both the baseline and global pruning approaches.

Model Architecture	Method	Accuracy (%)	Model Size (M)	FLOPs (G)	Inference Time (ms)
ResNet-18	Baseline	74.5	11.7	1.8	4.2
	Our Methodology	**75.2**	**6.2**	**1.0**	**2.8**
ResNet-50	Baseline	75.2	22.4	4.6	8.2
	Our Methodology	**76.1**	**9.8**	**2.1**	**5.3**
Vision Transformer	Baseline	73.8	86.6	12.4	15.6
	Our Methodology	**74.5**	**45.2**	**6.8**	**9.2**

Table 4. Scalability analysis across different model architectures. Our methodology achieves consistent improvements in accuracy, model size, FLOPs, and inference time.