Meta-Sparsity: Learning Optimal Sparse Structures in Multi-task Networks through Meta-learning

Anonymous authors
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Abstract

This paper presents meta-sparsity, a framework for learning model sparsity, basically learning the parameter that controls the degree of sparsity, that allows deep neural networks (DNNs) to inherently generate optimal sparse shared structures in multi-task learning (MTL) setting. This proposed approach enables the dynamic learning of sparsity patterns across a variety of tasks, unlike traditional sparsity methods that rely heavily on manual hyperparameter tuning. Inspired by Model Agnostic Meta-Learning (MAML), the emphasis is on learning shared and optimally sparse parameters in multi-task scenarios by implementing a penalty-based, channel-wise structured sparsity during the meta-training phase. This method improves the model's efficacy by removing unnecessary parameters and enhances its ability to handle both seen and previously unseen tasks. The effectiveness of meta-sparsity is rigorously evaluated by extensive experiments on two datasets, NYU-v2 and CelebAMask-HQ, covering a broad spectrum of tasks ranging from pixel-level to image-level predictions. The results show that the proposed approach performs well across many tasks, indicating its potential as a versatile tool for creating efficient and adaptable sparse neural networks. This work, therefore, presents an approach towards learning sparsity, contributing to the efforts in the field of sparse neural networks and suggesting new directions for research towards parsimonious models.

1 Introduction

Model sparsification and compression techniques in Deep Learning (DL) have become increasingly important not just for reducing computational cost, but also for improving the efficiency and interpretability of learned representations. While these methods are often motivated by the need to reduce model size or improve runtime on resource-constrained devices (Deng et al. (2020)), they also offer a powerful tool for feature selection and representation control within neural networks Hoefler et al. (2021). Techniques such as Neural Architecture Search (NAS) (Ren et al. (2021)), distillation (Hinton et al. (2015)), low-rank factorization (Sainath et al. (2013)), parameter sharing (Desai & Shrivastava (2023)), and sparsification (Hoefler et al. (2021)) have all contributed to this goal. This work focuses on two such techniques—parameter sharing, in the form of hard parameter sharing in Multi-Task Learning (MTL) (Caruana (1997); Ruder (2017); Vandenhende et al. (2021)), and sparsification—not purely for compression, but as a means of enabling adaptive feature sharing. In conventional MTL architectures with a shared backbone, multiple tasks are trained jointly by leveraging common intermediate representations. While this setup promotes knowledge transfer across tasks, it also introduces a significant challenge: all tasks are forced to use the same set of features, regardless of whether those features are equally relevant to each task. This indiscriminate sharing can lead to task interference, where features that are useful for some tasks negatively impact others. To address this, we propose to use sparsification not just to reduce model size, but to selectively sparsify the shared backbone—retaining only those parameters that are jointly beneficial across tasks. This results in more targeted and efficient feature sharing across tasks, along with learning a sparser (parameter-efficient) model.

Sparsification[1] in DL pertains to transforming a densely connected neural network or a dense model to a sparse one, where a considerable proportion of the parameters (typically model weights) are set to zero. This reduction of active weights leads to less computational load and memory usage during both the training and inference phases. Additionally, sparsification not only highlights the importance of key features (sparsity-driven feature selection) but also significantly enhances the model's ability to generalize to new data (Hoefler et al. (2021)). When implementing sparsity in Deep Neural Network (DNN), three key aspects must be considered: (i) identifying what elements should be made sparse, (ii) determining when to induce sparsity, and (iii) deciding on the method i.e., how to achieve sparsity. The article by Hoefler et al. (2021) offers a comprehensive survey that thoroughly explores these factors related to sparsity, among various other elements. Several elements can be sparsified in a DNN, like the parameters (or weights), neurons, filters in convolution layers, and heads in attention layers. Sparsification can be scheduled post-training, during training, or as sparse training, as illustrated in Figure 1. Further details on these methods are provided in the subsequent text. Various techniques can be employed to attain sparsity, including methods like magnitude pruning based on thresholds, sparsification based on input-output sensitivity, penalty-driven approaches, variational methods, and many more. In this work, we emphasize sparsifying the model parameters during the training by applying penalty-based (regularization-based) sparsification methods.

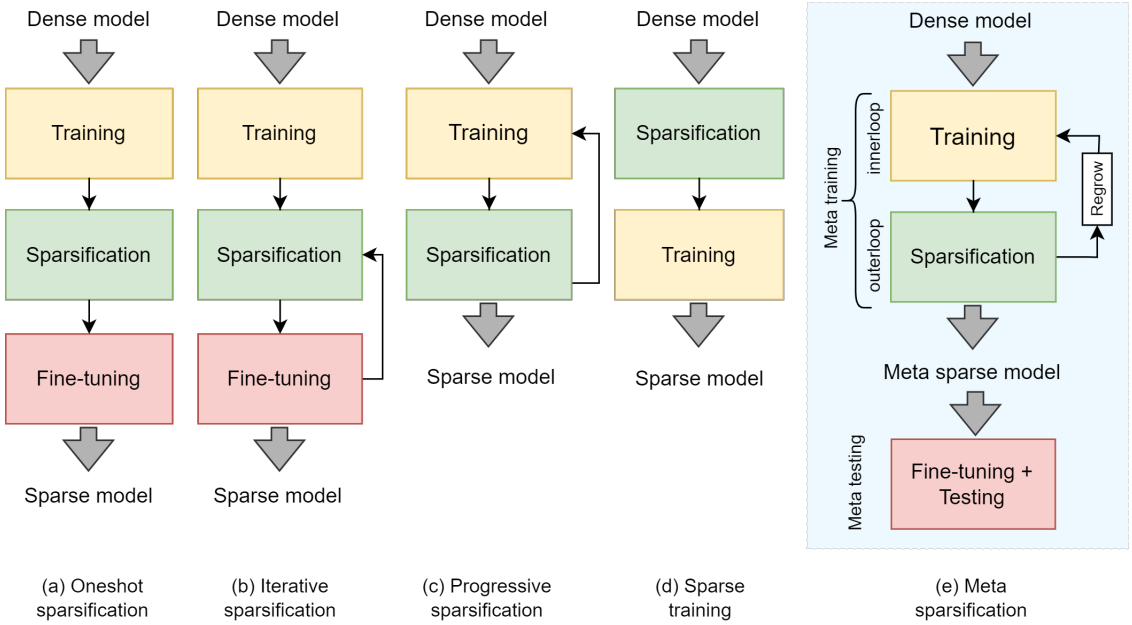


Figure 1: This figure illustrates (a-d) a few common approaches to achieving sparse models and (e) the proposed approach of meta-sparsification.

Various sparsity-inducing strategies have been developed to facilitate the transformation of a dense model into a sparse model (Hoefler et al. (2021)). However, a vital question that arises before implementing these strategies is determining when and how to apply sparsification. Figure 1 broadly illustrates some of these sparsity scheduling techniques as discussed by Hubens (2020). The one-shot sparsification (Figure 1(a)) is a fundamental technique that sparsifies an already trained dense model until a desired sparsity is achieved and then fine-tunes the sparse model. Fine-tuning allows the model to relearn. It helps to re-distribute the weights across the remaining parts of the network, ensuring that performance does not suffer significantly. Figure 1(b) shows iterative sparsification where sparsity is induced gradually over many steps (Han et al. (2015); Liu et al. (2017)). Only a handful of weights are eliminated at each iteration, and the network is fine-tuned to restore performance. This process is repeated multiple times. Zhu & Gupta (2017) presented

[1]*Note:* In the context of this work, *sparsification* should not be confused with *pruning*, which is also a widely used term in model compression. This is because both are different concepts; pruning is a technique that can help to achieve sparsification by systematically removing certain elements; sparsification is a much broader concept that can be reached through various methods, including but not limited to pruning. So the words sparsification and pruning are **not** used interchangeably.

the concept of automated progressive (or gradual) sparsification (Figure 1(c)) in their work, which is very similar to iterative sparsification. While both methods incrementally introduce sparsity into a dense network, automated gradual sparsification is different because it sparsifies the weights during the training of the model, allegedly claiming that it eliminates the necessity for subsequent fine-tuning. Figure 1(d) illustrates sparse training, where a sparse model is trained, and while training, it tries to retain the sparsity. This is often referred to as sparse-to-sparse training (Dettmers & Zettlemoyer (2019); Evci et al. (2020)), while the others Figure 1(a-c) are referred to as dense to sparse training.

In general, any sparsification involves the use of a few hyper-parameters that control the degree of sparsity, like thresholds in magnitude pruning, sparsification budget (or target), the regularization parameter in penalty-based sparsity approach, the dropout rate (probability), learning rate in gradual pruning, and several others. Often, approaches like grid search, random search, heuristic methods, etc, are employed to determine the optimal values of these crucial hyper-parameters. In MTL settings, selecting a fixed sparsity hyperparameter (e.g., regularization parameter in penalty-based sparsification) is especially challenging due to the varying degrees of feature sharing required by different task combinations. Manual tuning becomes inefficient, task-specific, and computationally expensive. We introduce a method to learn these hyper-parameters that induce sparsity through meta-learning. This work, therefore, proposes meta-sparsification, broadly depicted in Figure 1(e). In this work, we refer to it as *learning to learn sparsity*, or *learned sparsity*, or *meta-sparsity*. To be more precise, it is learning to learn or meta-learning (Finn et al. (2017)) the sparsity controlling hyper-parameter, thereby learning the sparsity pattern.

We begin with a dense multi-task model, which shares some layers i.e., a shared encoder or backbone between many tasks. To achieve a clear understanding, we begin by answering the three essential questions related to sparsification. (i) *What to sparsify?* - we aim to sparsify the parameters or weights of the model, primarily the parameters of the shared layers of a multi-task network. We apply channel-wise structured sparsity to the shared layers to achieve optimal shared representations across all the tasks. Structured sparsity is a coarse-grained approach that considers the architecture of the dense network while sparsifying i.e., for a Convolutional Neural Network (CNN); it involves zeroing out entire filters, neurons, or channels, basically a structured block of parameters. In contrast, unstructured sparsity is a more fine-grained approach that leads to scattered patterns of sparsity across the network by removing some parameters systematically. (ii)*how to achieve sparsity?* (i.e., the method) - we apply penalty-based (regularization-based) structured sparsity to the backbone of a multi-task network. The sparsification is applied in a setting inspired by *gradient-based meta-learning* e.g., Model Agnostic Meta Learning (MAML) (Finn et al. (2017)) to learn the meta-sparsity patterns across all the tasks. Meta-learning (Thrun & Pratt (2012); Huisman et al. (2021)), commonly referred to as 'learning to learn,' involves developing algorithms that learn from a variety of tasks and then apply the accumulated knowledge to enhance future learning of new or similar tasks. (iii) *when to sparsify?* - sparsity is applied while training the network; this is also known as *dynamic sparsity*. It refers to an approach where the sparsity pattern[2] changes over time during training, adapting to the evolving data and training requirements, while static sparsity refers to fixed sparsity patterns throughout training. The broader objective of this work is to explore learning the sparsity patterns across multiple learning episodes or tasks and to develop a meta-sparse model during the meta-training stage that can potentially be fine-tuned for the same tasks or unseen tasks in the meta-testing stage (as shown in Figure 1(e)). This not only enables dynamic adaptation of sparsity levels to task characteristics but also helps avoid over-sharing by tailoring feature usage in shared layers.

Now, the question is why this approach is applied in a multi-task context. Traditional MAML often involves tasks or learning episodes that are very similar or homogeneous; for example, all are image classification tasks (Hospedales et al. (2022); Upadhyay et al. (2024)). Because of this similarity, tasks may exhibit consistent sparsity patterns, hindering the meta-model's ability to accommodate a wider variety of tasks with different sparsity requirements. MTL, in contrast, enables the simultaneous learning of multiple, diverse tasks. Therefore, we aim to identify robust sparsity patterns that are suitable for various diverse tasks by

[2]*sparsity pattern* refers to the specific arrangement or layout of non-zero parameters within a model architecture, for example, a CNN when structured sparsity is applied. In the context of channel-wise structured sparsity, this pattern identifies the active (non-zero) channels within the network layers from the zeroed-out (inactive) ones. These patterns highlight the selective engagement of certain parts of the network while others remain dormant.

using sparsity in multi-task scenarios and learning sparse behavior across tasks through meta-learning. The main contributions of this work are as follows -

- *Learned sparsity framework called Meta-sparsity*: We introduce a novel approach that allows for the dynamic learning of sparsity in DNN. This is a significant shift from heuristic-based sparsity control to a more dynamic, task-aware method. Our method is versatile, being agnostic to model type, task, and sparsity type, allowing for wide applicability. Importantly, it presents sparsity as a mechanism for adaptive feature sharing rather than just compression.
- *Comprehensive evaluation:* We rigorously assess our approach across a variety of tasks using two publicly available datasets, showcasing its effectiveness. To provide comparative insights, we compare these results to those obtained from models using no sparsity and fixed-sparsity (i.e., the fixed value of sparsity hyper-parameter) in single-task and multi-task settings.
- *Robustness validation:* The robustness of our meta-sparse models is suggested by their ability to perform reasonably well on previously unseen tasks during meta-testing, showcasing their potential for adaptability.
- *Versatility in sparsity types:* Although this work focuses on channel-wise structured sparsity, we also validate the efficacy of our approach on unstructured sparsity, demonstrating its broad utility.
- *Direction for future research:* We conclude with a discussion on potential future directions and open questions to encourage more investigation in the areas of model sparsity.

Note that, while this work applies meta-sparsity within the context of MTL using hard parameter sharing, we clarify that the approach is not fundamentally restricted to MTL. It may, in principle, be adapted to single-task learning (STL) or other MTL variants (e.g., MTAN with task-specific modules (Liu et al. (2019))). However, such extensions would require significant changes. For instance, applying meta-learning to learn sparsity in STL is non-trivial because traditional bilevel meta-optimization (e.g., MAML) relies on multiple task episodes. Alternative meta-optimization paradigms (e.g., self-supervised meta-regularization or online bilevel training) would be needed. In the scope of this work, we adopt MAML as the underlying meta-learning strategy due to its strong theoretical foundations and demonstrated adaptability to unseen tasks. Our primary aim is to establish that sparsity can be effectively learned through gradient-based meta-optimization in multi-task settings. Importantly, the meta-sparsity approach is not tied to MAML. The framework is compatible with other gradient-based meta-learning algorithms, such as Meta-SGD (Li et al. (2017)), Reptile (Nichol et al. (2018)), or First-order MAML (Finn et al. (2017)), which could offer additional benefits in terms of computational efficiency or convergence behavior. These strategies may be incorporated with some adjustments to the optimization framework, as the core principle—learning sparsity-controlling parameters through meta-optimization—remains compatible across gradient-based meta-learning algorithms. However, an exploration of these alternatives is beyond the scope of this work and is left for future investigation.

This paper is structured as follows: Section 2 delves into the related work, setting the context and background for this study. Section 3 describes the methodology of the proposed approach. Section 4 details the experimental setup, while Section 5 presents the results, performance analysis, and a thorough discussion of the findings. Finally, Section 6 concludes the work and suggests many directions for future research.

2 Related work

This section focuses on research works that have employed the notion of learning diverse entities (i.e., hyper-parameters, optimizers, loss functions, and many more) through the utilization of black-box models or alternative methodologies. We additionally delve into the utilization of sparsity in deep learning and subsequently focus our attention on the application of sparsity in MTL networks. Finally, we position our work within the existing literature.

What can be learned?: The concept of learning to learn, commonly known as meta-learning, has been a learning paradigm of great interest in research for many years. This field has significantly advanced since the

seminal works of Schmidhuber (1987); Bengio et al. (1991); Thrun & Pratt (2012), leading to a wide range of applications. These algorithms aim to achieve generalization by learning from experiences, with the extent of generalization depending on the accumulation of meta-knowledge. In simple words, this generalization can be achieved by learning to learn parameters, hyper-parameters, loss functions, architectures, optimizers, and many more, which constitutes meta-knowledge. Many excellent studies have been conducted in this field of study; in order to set a context for our work, we will attempt to highlight and briefly discuss some of them.

We will first begin with *learning to learn parameter initialization*. Transfer learning centers on the concept of providing generalized initial parameters for the downstream task, enabling the fine-tuning of the new task with relatively fewer data samples. A possible approach to find the best initial parameters is to utilize meta-learning algorithms to train the parameters across different tasks, acquiring meta-knowledge that can aid in rapid adaption to new tasks. The article by Finn et al. (2017) presented MAML an algorithm that optimizes its parameters to facilitate adaptability and quick learning across a diverse range of tasks by providing a set of initial parameters. Reptile (Nichol & Schulman (2018)) is also a similar algorithm that is mathematically similar to first-order MAML, that learns the initialization of a network. First-order MAML (FOMAML) (Nichol et al. (2018)) and Almost No Inner Loop (ANIL) (Raghu et al. (2019)) are simplifications of MAML that provide computational advantages compared to MAML. The comprehensive survey by Huisman et al. (2021) provides detailed insights into other related work within the field of meta-learning.

While training neural networks, one of the most tedious tasks is hyperparameter tuning. This is because it involves a trial-and-error process over a vast, complex search space, and often, the hyperparameters are very use-case specific; there is no guarantee of finding the best solution, and each trial can be computationally expensive and time-consuming. That is why *learning to learn hyperparameters* is critical. Some works by Li et al. (2017); Xiong et al. (2022); Chen et al. (2023); Subramanian et al. (2023) focused on learning the learning rate or learning the learning rate schedules to train a deep learning model. Many articles learn to adapt all the hyperparameters, including the learning rate. For example, the article by Baik et al. (2020) adaptively generated per-step hyperparameters to improve the performance of the model. Bohdal et al. (2021) presented an approach for hyperparameter optimization by leveraging evolutionary strategies to estimate meta-gradients. Another similar work by Franceschi et al. (2018) offered a structured bi-level programming approach where the outer level updated hyper-parameters while the inner loop focused on task-specific learning or loss minimization. The approach presented by Franceschi et al. (2018) closely aligns with our work, with the primary distinction being our specific emphasis on learning structured sparsity within the framework of Multi-Task Learning (MTL) by employing MAML.

The articles by Wortsman et al. (2019); Gao et al. (2021); Bechtle et al. (2021); Gao et al. (2022b); Raymond et al. (2023a;b) aim to learn parametric loss functions, thereby *learning to learn a loss function*. On similar grounds, several works focus on *learned optimizers* or black-box or parametric optimizers, like the research by Bengio et al. (1991); Andrychowicz et al. (2016); Wichrowska et al. (2017); Lv et al. (2017); Li & Malik (2017); Shen et al. (2020); Harrison et al. (2022); Metz et al. (2022; 2020); Gao et al. (2022a). The learning-to-learn concept is also used in the field of neural architecture search (Elsken et al. (2019)) to achieve optimal architectures. This idea of *learned architectures* is discussed by Lian et al. (2019); Shaw et al. (2019); Elsken et al. (2020); Ding et al. (2022); Rong et al. (2023); Schwarz & Teh (2022a). Numerous studies in existing literature apply learning to learn concepts across various domains, such as reinforcement learning, attention learning, and neural memory learning, among others. However, this paper will not delve into each of these applications, as it is not intended to be a comprehensive review of the field. Instead, our primary objective is to highlight distinct insights and developments within a more limited domain of learning sparsity. Overall, it can be summarized that the black-box or parameterized models are increasingly replacing traditional white-box aspects of deep learning, such as loss functions, optimization algorithms, automated architecture search, and others. Building on this concept, this paper presents an approach to *learning to learn sparsity* using meta-learning.

Sparsification is one of the approaches for model compression in Deep Neural Networks (DNNs). It does not just reduce the complexity of the model but also leads to significant gains in performance, computation, and energy efficiency, all while strategically selecting key features that contribute to these gains. Hoefler et al. (2021) presented an elaborate study of sparsity in deep learning. They give an extended survey of works in this domain based on the types of sparsity, what can be sparsified, when to sparsify, and how to introduce

sparsity. Some other works that discuss model sparsity or pruning are Zhu & Gupta (2017); Gale et al. (2019). Our work is in line with the area of *learned sparsity*, in contrast to works achieving sparsity using fixed hyper-parameters. Most of the works in the domain focus on adaptive weight or parameter pruning (Han et al. (2015)), a technique to induce sparsity in a network. Kusupati et al. (2020) proposed a dynamic sparsity parameterization (STR) technique that used the sparse threshold operator to achieve sparsity in DNN weights by learning layer-specific pruning thresholds. Unlike the static (fixed) pruning methods, where the sparsity hyperparameter is fixed once pruning is performed, this method dynamically adjusts the sparsity hyperparameter during training, thereby determining the optimal sparsity pattern.

Another similar work by Carreira-Perpinan & Idelbayev (2018) introduced the learning-compression method, a two-stage process used by the algorithm to prune the network. In the learning phase, the weights are optimized e.g., reducing loss, while in the compression phase, network pruning is done using l_0 or l_1 constrain along with fixed pruning hyperparameters. Instead of manually adjusting the pruning rates of each layer, Zhou et al. (2021b) introduced ProbMask, a technique that leverages probability to determine the importance of weights across all layers and allows automatic learning of weight redundancy levels based on a global sparsity constraint. A combination of structured and unstructured sparsity is employed by Zhou et al. (2021a), resulting in N:M fine-grained sparsity wherein each group of M consecutive weights of the network, there are at most N weights that have non-zero values. So, this method does weight pruning based on the N:M budget. Many other works focus on adaptive pruning of networks or learning structured sparsity (Wen et al. (2016); Meng et al. (2020); Liu et al. (2018); Lee et al. (2021a); Wang et al. (2021); Upadhyay et al. (2023b)); however, none have applied meta-learning for learning to learn parameter sparsity. The articles contributed by Wen et al. (2016); Meng et al. (2020); Deleu & Bengio (2021) provide comprehensive insights into the concept of structured sparsity in deep neural networks. The idea of structured sparsity constitutes an essential aspect of our paper, and we draw significant inspiration from these works.

Recent studies have explored sparsity within meta-learning frameworks, primarily for compression or generalization in different learning settings. For instance, Lee et al. (2021b) and Schwarz & Teh (2022b) focus on learning sparse representations in the context of Implicit Neural Representations (INRs), targeting efficient signal adaptation. Schwarz & Teh (2022b), which is an extension of Lee et al. (2021b), introduces a pruning strategy where a shared sparse subnetwork is learned by applying a binary mask to the network weights during the inner loop of meta-learning. By pruning within each adaptation episode, the model achieves significant compression while maintaining performance across INRs. However, their objective remains focused on compression, whereas our work targets adaptive feature sharing in MTL through dynamic, task-aware sparsity learning. Similarly, Lee et al. (2021b) focuses on magnitude-based parameter pruning with a fixed budget for compression. Another work by Tian et al. (2020) proposes a meta-learning framework that applies network pruning to reduce overfitting in few-shot learning. While relevant in spirit, their approach focuses on single-task learning scenarios and uses fixed pruning budgets without adapting sparsity patterns dynamically. In comparison, our method uses penalty-based structured sparsity combined with gradient-based meta-learning to dynamically learn task-shared sparse structures that generalize across tasks in an MTL setup. While these works share the broader theme of integrating sparsity with meta-learning, their goals, formulations, and domains differ significantly from our proposed approach. We include them here for completeness and to highlight emerging intersections between meta-learning and sparsity.

Sparsity in multi-task learning: The domain of Multi-Task Learning (MTL) confronts two significant challenges. Firstly, as the number of tasks increases, the total number of trainable parameters also increases. Secondly, it is crucial to efficiently group similar tasks or effectively share features across tasks during training to prevent adverse information transfer among tasks, which could potentially impact the performance of certain tasks. Sparsity is used in the literature as one of the solutions to overcome these problems in multi-task settings. For example, Kshirsagar et al. (2017) constructed a regularization term to jointly optimize the task-specific parameters while also learning shared group structures (or parameters). Similarly, Gonçalves et al. (2016) in their work introduce Multi-task Sparse Structure Learning (MSSL) for joint estimation of per-task parameters and their relationship structure parameters using Alternating Direction Method of Multipliers (ADMM) algorithm (Boyd et al. (2011)). Argyriou et al. (2006), also assumed that tasks are related and used $l_1 - l_2$ regularization with the combined loss for efficient multi-task feature learning. Obozinski et al. (2010); Chen et al. (2009) used different sparse and non-sparse regularizations to learn the

low-dimensional subspace, which is shared by all the tasks. Sun et al. (2020a) proposed a method for iterative magnitude pruning of multi-task model parameters, which was inspired by the lottery ticket hypothesis (Frankle & Carbin (2019)). Their method induces unstructured l_1 type sparsity (sparse masks for weight matrices) by training sub-nets for multiple tasks until convergence.

Positioning our work: In the literature stated earlier, we looked into numerous ideas, such as learning to learn an optimizer, loss function, initial parameters, hyper-parameters, and many more. Building upon these discussions, we introduce an approach that utilizes meta-learning to facilitate the process of *learning to learn sparsity*. From the view of MTL, the previously mentioned studies induce sparsity in multi-task models by utilizing fixed values for regularization parameters, pruning thresholds, or sparsification budgets. In contrast to employing a trial-and-search methodology for the fixed hyper-parameter, the present study emphasizes acquiring the ability to learn a generalized sparsity parameter across many tasks. This approach can also be viewed as one of the strategies for optimal feature sharing among tasks within a multi-task framework facilitated by learned structured sparsity. To the best of our knowledge, this research direction has not been previously explored, offering a unique contribution to the fields of sparsity and MTL.

3 Methodology

In this section, we outline our proposed methodology. First, we will look into the conventional MTL, meta-learning with a focus on MAML, and group (structured) sparsity in order to establish a strong foundation for *meta sparsity*. This foundational discussion sets the stage for understanding the nuances of our approach. Furthermore, we also discuss a theoretical perspective of generalization in the context of this work.

3.1 Multi-task Learning

Multi-task learning (Caruana (1997)) is a very well-established learning paradigm wherein the aim is to jointly learn or train multiple related tasks. The underlying theory here is that the tasks help each other to learn better due to inductive transfer between the tasks, leading to improved performance and better generalization. A successful MTL can be achieved by establishing a balanced sharing between tasks, such that there is a positive transfer of information. This primarily depends on the parameter sharing approach used for MTL, which, according to Crawshaw (2020), can be either hard parameter sharing or soft parameter sharing. Hard parameter sharing is a result of the shared architecture, while soft parameter sharing can be achieved by applying constraints on the model parameters. These concepts, along with various research efforts in this area, are explored in a comprehensive survey on MTL by Crawshaw (2020). This work employs a very simple and conventional multi-task architecture, demonstrating hard-parameter sharing see Figure 2.

Consider a task distribution $p(T)$, from which, say, N non-identical yet related tasks are sampled that can be trained simultaneously in a multi-task setting, say, $\mathcal{T} = \{T_1, T_2, ..., T_N\}$. The objective of MTL is to train a multi-task model, say $f(\Theta)$ so that a combined loss ($\mathcal{L}$) of the task-specific losses $\{l_{T_1}, l_{T_2}, \ldots, l_{T_N}\}$ is minimized, such that the optimal parameters are given by the Equation 1,

$$\Theta^* = \arg\min_{\Theta} \mathcal{L}(f(\Theta)) = \arg\min_{\theta_b, \theta_i \in \Theta} \mathcal{F}_c(l_{T_i}(f_i(\theta_b, \theta_i))), \qquad i = 1, 2, \ldots N \tag{1}$$

where $\Theta = \{\theta_b\} \cup \bigcup_{i=1}^{N} \{\theta_i\}$, indicating that the set of multi-task parameters Θ comprises θ_b, the parameters of the shared architecture or backbone, and θ_i the parameters specific to each of the N tasks. f_i denotes the model designated for a particular task, consisting of a shared backbone (θ_b) along with layers specific to the task θ_i. $\mathcal{F}_c$ represents the function that combines or, more precisely, balances the N task-specific losses. This function may be a straightforward sum of losses, a weighted average, or any other tailored function designed to suit the specific requirements of the use case. To maintain fair learning across all tasks and to avoid any one task from dominating the learning process, loss balancing is essential in MTL. Several approaches to combine single-task losses to ease the multi-task optimization are discussed in Crawshaw (2020).

In this work, we employ the uncertainty weighting approach given by Kendall et al. (2018). The core idea of this approach is to optimize learning outcomes in multi-task contexts by prioritizing or weighing the tasks

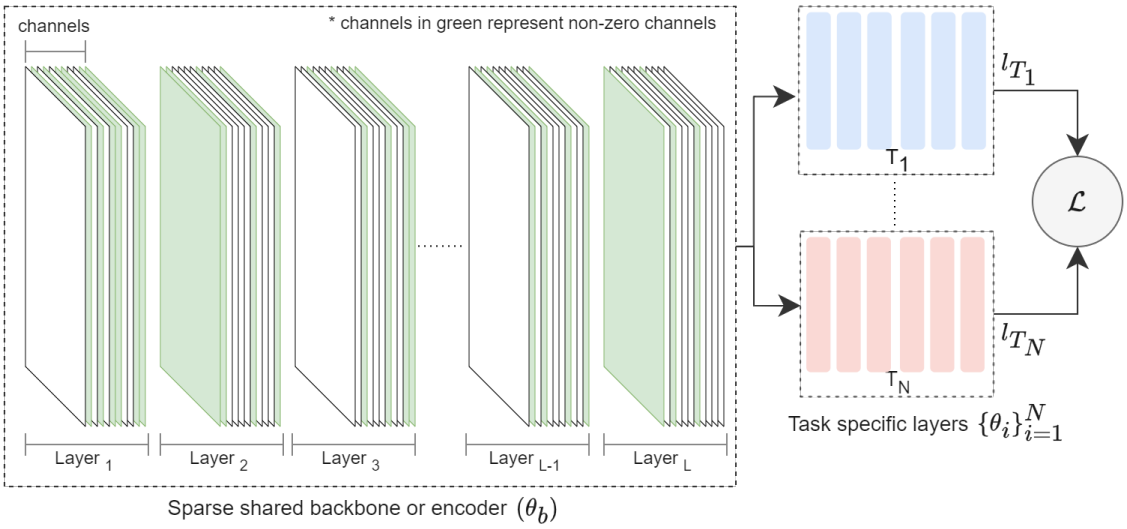


Figure 2: A schematic of the multi-task architecture used in this work (inspired by Upadhyay et al. (2023b)).

based on their uncertainty. It can mathematically be represented as,

$$\mathcal{L} = \mathcal{F}_c(l_{T_1}, l_{T_2}, \ldots, l_{T_N}) = \sum_{i=1}^{N} \left(\frac{1}{2\sigma_i^2} \cdot l_{T_i} + \log \sigma_i \right) \tag{2}$$

where σ_i is a learnable noise parameter for i^{th} task. This combined loss $\mathcal{L}$ undergoes backpropagation, where gradients of the loss are computed with respect to all model parameters Θ, encompassing both shared and task-specific parameters. These gradients are then used to update Θ to minimize $\mathcal{L}$ by finding the optimized parameters, thereby enhancing the performance of all tasks. Algorithm 1 outlines the practical implementation of Multi-Task Learning (MTL).

Algorithm 1 Multi-Task Learning (MTL)

Require: Sample N tasks from a task distribution $p(T)$, say $\mathcal{T} = \{T_1, T_2, ...T_N\}$
Require: MTL model with parameters, $\Theta = \{\theta_b\} \cup \bigcup_{i=1}^{N} \{\theta_i\}$ ▷ where θ_b = shared parameters and θ_i = task-specific parameters
while not converged **do**
  for $b_s = 1$ **to** number of batches in dataset D **do**
    Sample a batch of data for each task T_i ▷ training data for all tasks
    Compute task-specific losses, l_{T_i}, for each task T_i
    Compute multi-task loss, $\mathcal{L}_{MTL} = \mathcal{F}_c(l_{T_1}, l_{T_2}, ..., l_{T_N})$ ▷ aggregation of task-specific losses
    Compute gradients, $g = \nabla_\Theta \mathcal{L}_{MTL}$
    Update parameters, $\Theta \leftarrow \Theta - \alpha \cdot g$ ▷ α is the learning rate
  end for
end while

3.2 Meta-learning

Meta-learning, often known as 'learning to learn' (Thrun & Pratt (1998); Baxter (1998)), is a learning algorithm that leverages past learning experiences to enhance the performance of a new task. In conventional Machine Learning (ML), an algorithm is designed to acquire knowledge from a given dataset to perform a specific task. However, meta-learning goes a step further; it involves algorithms that can evaluate their learning process, analyze their performance across various tasks, and leverage this insight to learn new tasks more

efficiently. Meta-learning algorithms can be classified into three categories, i.e., (i)model-based, (ii)metric-based, and (iii)optimization-based or gradient-based meta-learning. These classifications are thoroughly discussed in several survey papers, including works by Huisman et al. (2021); Tian et al. (2022); Hospedales et al. (2022), and many more, which provide in-depth analyses and comparisons of methodologies within each category. Out of these, in this work, we focus on optimization or gradient-based meta-learning algorithms, particularly MAML (Finn et al. (2017)). MAML facilitates fast and efficient adaptation of a DNN to new and distinct tasks, using only a limited amount of training data. This is accomplished by optimizing a set of initial parameters that are highly adaptable and enable quick fine-tuning via minimal gradient updates. This approach improves model generalizability and performance and has been thoroughly tested in a variety of settings (tasks), such as classification, regression, and reinforcement learning. In this work, we extend its application beyond similar or homogeneous tasks to dense prediction tasks like segmentation, depth estimation, and others by incorporating MTL in the form of multi-task learning episodes (Upadhyay et al. (2023a) of heterogeneous tasks [3].

The MAML framework works with many tasks, also defined as learning episodes, and progresses through two hierarchical levels (or loops): the inner loop, focusing on learning from individual tasks through rapid adaptation to training data, and the outer loop, which aggregates knowledge from numerous tasks to enhance and accelerate the adaptation process. These levels are formalized in the form of a bilevel optimization problem in MAML in the meta-training stage, which is addressed hereafter. After meta-training, the 'learning to learn' stage, new tasks can be introduced in the meta-testing stage, also known as the 'adaptation stage.' Consider, for N tasks or learning episodes sampled from task distribution $p(T)$, $\mathcal{L}_{meta}$ and l_{T_i} be the meta (i.e., outer) and i^{th} task-specific (i.e., inner) loss functions respectively. Along the same lines, as formulated in Section 3.1, let Θ_{meta} be the meta parameters, while θ_i be the parameters for i^{th} task. For training, the dataset for N tasks can be expressed as $\mathcal{D} = \{(D_{sup_1}, D_{query_1}), \ldots, (D_{sup_N}, D_{query_N})\}$, where D_{sup} stands for support set and D_{query} stands for the query set such that $D_{sup_i} \cap D_{query_i} = \emptyset$. The bi-level optimization in MAML, where one optimization problem involves another as a constraint (Hospedales et al. (2022); Huisman et al. (2021); Finn et al. (2017)), can be written as follows :

$$\Theta^*_{meta} = \arg\min_{\Theta_{meta}} \sum_{i=1}^{N} \mathcal{L}_{meta}(\theta^*_i, \Theta_{meta}, D_{query_i}) \qquad (outer\ loop) \tag{3}$$

$$where, \quad \theta^*_i \equiv \theta^*_i(\Theta_{meta}) = \arg\min_{\theta} l_{T_i}(\theta, \Theta_{meta}, D_{sup_i}) \qquad (inner\ loop) \tag{4}$$

Algorithm 2 outlines the implementation of the above-discussed meta-learning, particularly the bi-level optimization of MAML. So, Θ_{meta} can be generalized initialization of model parameters; it can also be hyperparameters such as learning rate, regularization parameter, or parameterized loss functions. This work aims to concurrently 'learning to learn' the structured sparsity regularization parameter along with the multi-task model parameters that offer a suitable initial point for model training in the meta-testing stage. Further details are provided in Section 3.4.

3.3 Group sparsity

This section introduces group sparsity, specifically $l_1 - l_2$ regularization, as an important building block of the meta-sparsity framework. This discussion is not a new contribution; rather, it gives the theoretical context which is necessary for laying the groundwork for the proposed methodology outlined in Section 3.4.

Sparsity in DL can be introduced in two broad ways: as model sparsity, affecting the model structure, or as ephemeral sparsity, impacting individual data examples, as discussed by Hoefler et al. (2021). As already discussed in Section 1, this work explores model sparsity, especially regularization(penalty)-based model weight sparsification. In the context of how sparsity is introduced to model parameters, two distinct modes emerge - structured and unstructured sparsity. Unstructured sparsity (also known as fine-grained sparsity), the more straightforward method, eliminates the least significant weights based on chosen criteria, leading

[3]As defined by Upadhyay et al. (2024), tasks are considered homogeneous when they share similar objective, and if the objectives differ, they are classified as heterogeneous. For example, if the objective of all the tasks is image classification, they can be referred to as homogeneous tasks.

Algorithm 2 Model-Agnostic Meta-Learning (MAML)

Require: Sample N tasks from a task distribution $p(\mathcal{T})$, say $\mathcal{T} = \{T_1, T_2, \ldots, T_N\}$
Require: Initialize meta-parameters Θ_{meta} ▷ initial shared model parameters
  while not converged **do**
    Initialize gradient accumulator $\mathcal{G} \leftarrow [\ ]$ ▷ empty list for gradient accumulation
    for each task $T_i \in \mathcal{T}$ **do** ▷ inner loop for task-specific adaptation
      Sample support set D_{sup_i} and query set D_{query_i}
      Compute task-specific loss $\mathcal{L}_{T_i}$ on D_{sup_i} ▷ use support data for task-specific training
      Update $\Theta_{T_i} \leftarrow \Theta_{meta} - \alpha_{in} \cdot \nabla_{\Theta_{meta}} \mathcal{L}_{T_i}$ ▷ perform one or more gradient steps, α_{in}: inner loop learning rate
      Compute meta-loss gradient $G_i \leftarrow \nabla_{\Theta_{T_i}} \mathcal{L}(\Theta_{T_i}, D_{query_i})$ ▷ gradient on query set
      Accumulate gradient $\mathcal{G} \leftarrow \mathcal{G} \cup \{G_i\}$
    end for
    Compute aggregated meta-gradient $\mathcal{G}_{meta} = \text{Average}(\mathcal{G})$ ▷ aggregate gradients from all tasks
    Update $\Theta_{meta} \leftarrow \Theta_{meta} - \alpha_{out} \cdot \mathcal{G}_{meta}$ ▷ outer loop meta-update, α_{out}: outer loop learning rate
  end while

to irregular sparse patterns. In contrast, structured sparsity (also known as group sparsity) adopts a more holistic strategy by targeting the elimination of whole groups of parameters. In this context, a *group* refers to various structural elements within the model, such as channels, filters, neurons, tailored blocks, or attention heads, each representing a distinct set of parameters (Hoefler et al. (2021); Liu & Wang (2023)). Unstructured sparsity can significantly reduce the model size but typically achieves only modest speedups on hardware for dense computations, such as GPUs. Meanwhile, structured sparsity is designed to complement optimized hardware architectures, leading to improvements in computational efficiency. This work primarily concentrates on structured sparsity, utilizing penalty-based techniques for model weight sparsification. Additionally, while our approach centers on structured sparsity, we have also implemented it for unstructured sparsity. The findings and insights are discussed in Section 5.

Suppose the weights of a model are divided into G non-overlapping groups of varying sizes, denoted as $\Theta = \{\theta^1, \theta^2 \ldots \theta^G\}$. $\mathcal{L}(f(\Theta))$ represents the loss function, where $f(\Theta)$ represents the model with parameters Θ. The objective function for the regularization-based group sparsity (group lasso) given by Yuan & Lin (2005) can be expressed as -

$$\Theta^* = \arg\min_{\Theta} \quad \mathcal{L}(f(\Theta)) + \underbrace{\lambda \sum_{g=1}^{G} \sqrt{n^g}\ ||\theta^g||_2}_{l_1 - l_2 \text{ norm regularization term:} \mathcal{R}} \qquad where \quad \theta^g \in \Theta \tag{5}$$

where $\mathcal{R}$ is the regularization term that zeros out entire groups of parameters denoted by θ^g. Here, n^g is the number of elements in the gth group, such that $n^g > 1\ \forall g$, it is multiplied to achieve normalization of the regularization term across groups of varying sizes. The l_2 norm of the parameter group is represented by the term $||\theta^g||_2 = \sqrt{\sum_j (\theta^g_j)^2}$, here θ^g_j is the parameter at index j for group g. In Equation 5, the regularization parameter is represented by λ, which controls the degree of sparsity by balancing the trade-off between model complexity and data conformity. We aim to learn this hyperparameter using MAML in meta-sparsity over multiple tasks. Given the regularization term $\mathcal{R}$ combines the l_1 norm of l_2 norms across groups, it is often referred to as $l_1 - l_2$ norm in this work.

To optimize the composite loss function in Equation 5, proximal gradient methods can be applied since the regularization term $\mathcal{R}$ is non-differentiable (Parikh et al. (2014); Bach et al. (2012)). The proximal gradient descent updates the parameters based on the gradient of the differential part of the composite loss function given by

$$\Theta_{t+1} \leftarrow prox_{\alpha\mathcal{R}}(\Theta_t) = prox_{\alpha\mathcal{R}}(\Theta_t - \alpha \nabla_{\Theta} \mathcal{L}(f(\Theta_t))). \tag{6}$$

Here, $prox_{\alpha\mathcal{R}}$ is the proximal operator, and α is the learning rate. Since Θ is divided into G disjoint groups, the proximal operator can be written as,

$$prox_{\alpha\mathcal{R}}(\Theta) = (prox_{\alpha\mathcal{R}}(\theta^1), \ldots, prox_{\alpha\mathcal{R}}(\theta^g), \ldots, prox_{\alpha\mathcal{R}}(\theta^G)) \tag{7}$$

In the case of group sparsity-inducing regularization, this proximal operator can be computed and has a closed form as discussed by Combettes & Wajs (2005); Hastie et al. (2015); Scardapane et al. (2017); Deleu & Bengio (2021), given by the equation,

$$prox_{\alpha\mathcal{R}}(\theta^g) = \begin{cases} \left[1 - \frac{\alpha\lambda\sqrt{n^g}}{||\theta^g||_2}\right]\theta^g & ; ||\theta^g||_2 > \alpha\lambda\sqrt{n^g} \\ 0 & ; ||\theta^g||_2 \leq \alpha\lambda\sqrt{n^g} \end{cases} \tag{8}$$

So, if the l_2 norm of a group of parameters is less than (or equal to) a threshold depending on the size of the group and regularization parameter, the entire group of parameters is zeroed out, thereby enforcing group sparsity.

3.4 Proposed approach - Meta sparsity

Now that we have established the concepts of MTL, meta-learning, and group sparsity, we will discuss the proposed approach of meta-sparsity or learned sparsity in this section. Now, in the context of this work, to precisely answer the three questions related to sparsity- (i) *what to sparsify?*: the objective is to sparsify the backbone parameters i.e., θ_b, also known as the shared layers of the multi-task network. (ii) *how to sparsify?*: apply group sparsity (i.e., Equation 5) to the backbone parameters θ_b only. The channels of the convolution layer weight matrix are treated as different groups, i.e., $\theta_b^l(:, c, :, :)$ which represents one group consisting of the weights of cth channel of the lth layer. This is symbolically illustrated in Figure 2. (iii) *when to sparsify?*: this proposed approach is inspired by meta-learning i.e., learning to learn sparsity; therefore, the sparsification is done during the meta-training phase in the outer loop. This approach, in general, can be viewed as a *learning-sparsification* iterative methodology. It involves episode-specific learning at the inner loop (Equation 4) and parameter sparsification at the outer loop (Equation 3) of MAML in an iterative manner. Therefore, similar to meta-learning, meta-sparsity also has two phases: the meta-learning phase and the meta-testing (adaptation) phase. An overview of the meta-training and testing stages is given in the table below. Adding one more question to the ones above, (iv) *why sparsification?*: besides model compression, the main intention behind applying structured sparsity is efficient feature selection across multiple tasks. Furthermore, sparsification promotes generalization, an important aspect when incorporating new yet related tasks into the multi-task framework.

Since MAML is an episodic learning approach (Hospedales et al. (2022); Finn et al. (2017)), it necessitates several learning episodes, which essentially involve single-task learning. In this study, we extend the concept of learning episodes to include multi-task learning episodes (Upadhyay et al. (2023a)), encompassing all possible combinations of the N tasks. Therefore, the episodes are comprised of both single tasks and multi-task combinations, as expressed in Equation 9. The motivation behind using multi-task learning episodes, as opposed to only single-task episodes, is rooted in the hypothesis that grouping tasks during training enables the model to effectively capture shared representations and task relationships. Unlike traditional meta-learning episodes, which typically focus on single-task adaptation, multi-task episodes allow the model to learn how to handle varied task combinations. This design choice aims to:

1. Exploit task relationships: Combining tasks in episodes helps the model understand shared representations and interactions, enhancing its ability to balance competing objectives.
2. Enhance generalization: Training over diverse multi-task episodes improves the model's capability to generalize to unseen task combinations.
3. Learn meta-knowledge across task combinations: Constructing episodes with multiple tasks enables the meta-optimization process to learn not just individual tasks but also their interactions, facilitating better transfer to new task groupings.

For N tasks i.e., $\mathcal{T} = \{T_1, T_2, \ldots, T_N\}$, the learning episodes $\mathcal{E}$ used for meta-training are an ensemble of single-task and multi-task learning episodes given by the power set of $\mathcal{T}$, such that,

$$\mathcal{E} = 2^{\mathcal{T}} \setminus \{\emptyset\} = \{E_1, E_2, ..., E_{2^N-1}\} = \{T_1, T_2, .., T_1T_N, .., T_1T_2T_N, ...\} \tag{9}$$

The training procedure is inspired by MAML(Finn et al. (2017)) but with two notable distinctions. First, the training process involves a multi-task model being trained on single-task and multi-task learning episodes to utilize sparsity patterns specific to each context; Second, in addition to the model parameters, the hyperparameter that induces sparsity, denoted as λ, is also meta-learned, which results in a meta-sparse multi-task model.

META-TRAINING		**META-TESTING**
	Inner loop *(learning)*	**Fine-tuning** (*similar to MTL*)
Objective:	reduce the episode-specific loss i.e. $\mathcal{L}_{E_i}$	*Begin with - Meta sparse multi-task model* Three possibilities:
Train:	episode-wise training of multi-task model with sparse backbone	(i) Fine-tuning on all the same N tasks as meta-training.
Optimize:	multi-task model parameters(Θ_{E_i}) for every learning episode.	(ii) Add new task and fine-tune only on the new $(N+1)^{th}$ task
	Outer loop *(sparsification)*	(iii) Add new task and fine-tune on all the (N+1) tasks.
Objective:	reduce the meta-loss i.e. $\mathcal{L}_{meta}$	*(maintain sparsity while fine-tuning)*
Train:	meta-train the multi-task model on all learning episodes.	**Testing**
Optimize:	multi-task model parameters(Θ_{meta}), regularization parameter(λ_{meta}) (inducing channel-wise sparsity)	Use an independent test set to evaluate the performance of the meta-sparse multi-task model
Outcome:	Meta sparse multi-task model	

In CNN, the weight tensor is organized as a 4D array, with dimensions representing the number of filters, channels(or depth), height, and width. When considering structured sparsity, the specific structures that can be regularized include filters, channels, filter shapes, or a customized block of parameters. In this work, we employ channel-wise structured sparsity to the shared backbone of the multi-task architecture. Several previous studies, including those by Wen et al. (2016); Deleu & Bengio (2021); Upadhyay et al. (2023b), among others, have focused on channel-wise sparsity across a range of applications, mainly because of two reasons. First, this approach generates smaller dense networks by eliminating redundant channels, effectively compressing the network. Furthermore, these optimized networks offer greater hardware benefits, especially for GPUs, as they can be more easily accelerated. The emphasis on channel-wise sparsity improves both computing efficiency and the suitability of models for deployment on devices with limited resources.

Consider a simple and conventional multi-task architecture with a shared encoder or backbone: a CNN and N task-specific networks (a.k.a heads) connected to the backbone. In this case the multi-task model parameters $\Theta = \{\theta_b\} \cup \bigcup_{i=1}^{N} \{\theta_i\}$ where θ_b are the shared parameters and θ_i are the task-specific parameters for i^{th} task. Since the group sparsity is applied to the channels of convolution layers of the backbone network, the meta-optimization objective as per Equation 3 and 4 can be expressed along with group sparsity (Equation 5) as,

$$\Theta^*_{meta} = \underset{\Theta_{meta}}{\arg\min} \sum^{N_b} \mathcal{L}_{meta}(\Theta^*_{E_i}, \Theta_{meta}, D_{query_{E_i}}) + \lambda \sum_{g=1}^{G} \sqrt{n^g} ||\theta^g_{b_{E_i}}||_2, \quad s.t.\ E_i \in \mathcal{E} \quad (outer\ loop) \tag{10}$$

$$where, \quad \Theta^*_{E_i} \equiv \Theta^*_{E_i}(\Theta_{meta}) = \underset{\Theta_{E_i}}{\arg\min}\, \mathcal{L}_{E_i}(\Theta_{E_i}, \Theta_{meta}, D_{sup_{E_i}}). \qquad (inner\ loop) \tag{11}$$

$$\sum_{g=1}^{G} \sqrt{n^g}\ ||\theta^g_{b_{E_i}}||_2 = \sum_{l=1}^{L} \sum_{c=1}^{C_l} \sqrt{numel(\theta^l_{b_{E_i}}(:,c,:,:))}\ \ ||\theta^l_{b_{E_i}}(:,c,:,:)||_2 \quad (l_2\ norm\ of\ a\ group). \tag{12}$$

Here, L is the number of convolution layers, and C_l is the number of channels in the lth layer. $numel(\cdot)$ represents the number of elements in the vector. N_b represents the total number of batches of data in batch-wise training of the model. λ is the learnable regularization parameter. E_i stands for the learning episode see Equation 9 Here, $\mathcal{L}_{E_i}$ is the episode-specific loss if the learning episode has a single task, then $\mathcal{L}_{E_i} = l_{T_j}$

such that, $T_j \in \mathcal{T}$. But if it is a multi-task episode, say the $\mathcal{L}_{E_i} = \mathcal{F}_c(l_{T_a}, l_{T_b}, l_{T_c})$, where $T_a, T_b, T_c \in \mathcal{T}$ (see Equation 1). To avoid the potential divergence of λ towards negative infinity, a Softplus function is applied to λ, which ensures that it remains positive throughout the optimization process. The Softplus function, defined as $\text{Softplus}(x) = \frac{1}{\beta}\log(1 + \exp(\beta \cdot x))$, acts as a smooth approximation to the ReLU function and effectively constrains λ to positive values.

The Equation 10 and 11 illustrate the process of bi-level optimization. The inner loop trains the multi-task model for various task combinations, while the outer loop finds the meta-optimized multi-task network parameters and generates a channel-sparse backbone network. This process involves meta-learning the channel sparsity and model parameters. The full algorithm of meta-training is outlined in Algorithm 3. This algorithm is built on the principles of MTL (Algorithm 1) and MAML (Algorithm!2). It combines MTL's ability to optimize shared and task-specific parameters with MAML's meta-optimization framework, enabling the dynamic learning of both model parameters (Θ_{meta}) and the sparsity-inducing hyperparameter (λ_{meta}). Note that λ_{meta} is simply a representation of λ being meta-learned; technically, both are the same.

Algorithm 3 Meta-sparsity (training)

Require: Sample N tasks from a task distribution p(T), say $\mathcal{T} = \{T_1, T_2, ...T_N\}$
Require: MTL model with parameters, $\Theta = \{\theta_b\} \cup \bigcup_{i=1}^{N}\{\theta_i\}$ ▷ where θ_b = shared parameters and θ_i = task-specific parameters
Require: Initialize meta parameters Θ_{meta} and λ_{meta} ▷ dense model and sparsity hyperparameter
Require: Single & multi-task episodes: $\mathcal{E} = \{E_1, E_2, .., E_{2^N-1}\}$
  while not converged **do**
    for $b_s = 1$ **to** no. of batches of D_{sup} and D_{query} **do** ▷ *outer loop*
      Randomly sample an episode E_i
      $\mathcal{G} \leftarrow [\ ]$ ▷ Using [ ] to denote an empty list
      Initialize $\Theta_{E_i} \leftarrow \Theta_{meta}$
      if Θ_{E_i} has sparse groups and regrow probability $r_p > 0$ **then** ▷ Regrowing sparse parameters
        - Select groups for regrowth (randomly or some criteria))
        - Initialize the selected groups
      end if
      for κ inner updates **do** ▷ *inner loop*
        if E_i contains n tasks such that, $n > 1$ **then**
          $\mathcal{L}_{E_i} = \mathcal{F}_c(l_{T_1}, l_{T_2}, \ldots, l_{T_n})$ ▷ multi-task loss
        else
          $\mathcal{L}_{E_i} = l_{T_j}$ ▷ single task loss
        end if
        Calculate gradients, $g = \nabla_{\Theta_{E_i}} \mathcal{L}_{E_i}(\Theta_{E_i}, \Theta_{meta}, D_{sup_{E_i}})$
        Update $\Theta^*_{E_i} \leftarrow \Theta_{E_i} - \alpha_{in}\ g$ ▷ α_{in} is the learning rate for adaptation stage
      end for
      For the query set, calculate $G_i = \nabla_{\Theta^*_{E_i}} \mathcal{L}_{meta}(\Theta^*_{E_i}, \Theta_{meta}, D_{query_{E_i}})$
      Accumulate gradients, $\mathcal{G} \leftarrow \mathcal{G} \cup \{G_i\}$ ▷ gather gradients for all the learning episodes
    end for
    Calculate meta gradients, $\mathcal{G}_{meta}$, as the average of all accumulated gradient
    Update $\Theta^*_{meta} \leftarrow prox_{\alpha_{out}}(\Theta_{meta} - \alpha_{out}\ \mathcal{G}_{meta,\Theta})$ ▷ meta-update for model parameters where α_{out} is the learning rate for meta stage (outer loop)
    Update $\lambda^*_{\text{meta}} \leftarrow \lambda_{\text{meta}} - \alpha_{\text{out}}\ \mathcal{G}_{meta,\lambda}$ ▷ meta-update for λ_{meta}
  end while

Within the meta-training inner loop, the concept of regrowth can also be introduced, which involves reinstating previously pruned (or sparsified) parameters, as highlighted by (Hoefler et al. (2021)). This strategy is employed because regrowth aids in overcoming excessive sparsification, enables the model to adjust to new data patterns, and ensures a balance between achieving sparsity and maintaining performance (Sun et al. (2023); Zhang et al. (2024)). Moreover, the literature suggests that when regrowth is iteratively used along with sparsity (or pruning), it contributes to discovering better parsimonious network architectures. The extent of parameter regrowth is modulated by a hyper-parameter r_p that governs the probability of regrowth. Regrowth can be implemented in the inner loop during meta-training in order to enhance episode-specific

learning in this work. We did not apply regrowth to all trials to avoid influencing the outcome of meta-sparsity. However, we included some results for comparison in Section 5 (under the subheading - Regrowing the parameters).

In meta-testing, we have the meta sparse multi-task model, which is further fine-tuned (as discussed in Figure 1(e)). A new task may be introduced during this stage to evaluate the generalizability of the meta-model. During fine-tuning, the sparsity pattern of the backbone parameters is maintained, and only the task-specific heads of the new tasks are trained. This is similar to standard multi-task training (Equation 1). Once we have the fine-tuned multi-task model, its performance is evaluated on the test set.

During meta-training, the coupling between the sparsity-inducing hyperparameter λ and the model parameters θ_b is a fundamental property of the group lasso regularization, as expressed by Equation 8. As the equation shows, the degree of shrinkage (and potential zeroing-out) of a parameter group θ^g directly depends on the current value of λ. This demonstrates that any changes in λ affect not just the magnitude of the regularization penalty, but also the structure of the learned parameters. Rather than being a drawback, this interaction is leveraged by our framework to enable task-adaptive sparsity, where λ evolves during meta-training in response to how shared features contribute across task episodes.

In this study, we primarily emphasize meta-learning structured ($l_1 - l_2$) sparsity for the shared layers in a multi-task setting. However, through extensive experiments, we demonstrate that our approach is not limited to structured sparsity alone; it is equally adept at meta-learning other forms of penalty-based sparsity, such as l_1 (unstructured) sparsity. For this work, we limit the focus of our work only to regularization (or penalty) based sparsity-inducing approaches. However, we are certain that the proposed approach has broader applications and can facilitate learning sparsity in various elements, including weights, activations, or any aspect that can be adjusted via a hyperparameter. Furthermore, the learning process involves various hyperparameters, such as learning rate, momentum, activation functions, and dropout probability, which can also be optimized through meta-learning. However, this paper focuses on meta-learning the model parameters and the regularization hyperparameter. This focused approach will allow us to thoroughly examine the sole influence of learning sparsity on model performance.

3.4.1 Behavior of λ during meta-optimization

In our approach, the total meta-objective given in Equation 10 includes a sparsity-inducing regularization term weighted by a hyperparameter λ-

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{meta}}(\Theta) + \lambda\,\mathcal{R}(\theta_b), \tag{13}$$

where $\mathcal{R}(\theta_b)$ is the structured sparsity regularization term applied to the shared backbone parameters, and Θ includes both shared and task-specific parameters. At first glance, it may appear that the gradient with respect to λ would always push it to decrease since differentiating the regularization term yields:

$$\frac{\partial \mathcal{L}_{\text{total}}}{\partial \lambda} = \mathcal{R}(\theta_b), \tag{14}$$

which is always non-negative. However, θ_b itself depends on λ, as it is optimized jointly with it during meta-training. Therefore, the total derivative of the loss with respect to λ must include both explicit and implicit gradient terms, as follows:

$$\frac{d\mathcal{L}_{\text{total}}}{d\lambda} = \frac{\partial \mathcal{L}_{\text{total}}}{\partial \lambda} + \frac{\partial \mathcal{L}_{\text{total}}}{\partial \theta_b} \cdot \frac{d\theta_b}{d\lambda}. \tag{15}$$

This second term captures how changes in λ indirectly affect the model through the shared parameters θ_b. If decreasing λ leads to worse task performance (i.e., an increase in $\mathcal{L}_{\text{meta}}$), the gradient flow through θ_b can act as a counterbalance and push λ to increase again. This behavior provides a feedback mechanism that helps stabilize λ. This kind of interaction is well studied in hyperparameter optimization and meta-learning

literature, particularly in bilevel optimization frameworks, where such dependencies are explicitly modeled and exploited. We refer the reader to Franceschi et al. (2018) for a detailed discussion of this principle.

In practice, during meta-training, λ starts inducing sparsity while also improving performance. As training progresses, the optimization dynamics and performance trade-off cause the sparsity level to stabilize naturally (see Figure 7). A very small λ would harm performance, so the optimizer avoids pushing it further down. Additionally, the use of a softplus transformation on λ ensures it stays positive and updates smoothly. We also use early stopping based on validation loss, which prevents overfitting and further helps to maintain a meaningful value for λ.

These factors—gradient feedback through θ_b, softplus activation, and early stopping—prevent λ from collapsing to zero or growing excessively. This ensures the algorithm avoids trivial solutions and maintains an effective level of sparsity throughout training.

3.5 A theoretical perspective on generalization

In ML and DL, generalization refers to the ability of a model to adapt to new, previously unseen data, usually from the same distribution as training data (Goodfellow et al. (2016)). This work encompasses three key concepts, i.e., MTL, meta-learning, and sparsification, particularly group sparsity, and all of these contribute towards generalization in their way, as summarized in Table 1. This subsection explains the concept of generalization in terms of all the important components of this work that aid in establishing the theoretical foundation for generalization in the proposed meta-sparsity approach.

Table 1: Generalization types and their impact w.r.t. meta-learning, MTL, and Sparsification

Paradigm	**Type of Generalization**	**Impact**
Meta-Learning	Task-Level	Learns to adapt to new tasks by capturing shared patterns across a distribution of tasks.
	Distribution-Level	Models the task distribution, enabling effective transferability to tasks drawn from similar distributions.
MTL	Task-Level	Leverages shared representations to enhance performance across related tasks.
	Data-Level	Exploits cross-task data regularization to prevent overfitting and improve learning from limited data.
Sparsification	Feature-Level	Prunes redundant parameters to focus on task-relevant features, reducing overfitting and enhancing generalization to unseen data.

Theoretically, the combination of MTL, meta-learning, and sparsification establishes a robust framework for achieving generalization. For cross-task generalization (task-level and distribution-level), MTL facilitates the learning of task-invariant representations by leveraging shared knowledge across tasks. Meta-learning enhances adaptability to new tasks by optimizing model parameters across a distribution of tasks, which acts as a good initialization for a new task. Additionally, sparsification focuses on essential shared features, thereby reducing overfitting to specific tasks. For within-task generalization (data-level, feature-level), MTL acts as a regularizer by utilizing multi-task data, mitigating overfitting on individual tasks (Caruana (1997); Crawshaw (2020)). Meta-learning further ensures efficient adaptation to new, unseen data within a task by identifying generalizable priors (Hospedales et al. (2022); Huisman et al. (2021)). Meanwhile, sparsification reduces noise and retains only the most critical connections, simplifying the model and enhancing its performance on novel data (Hoefler et al. (2021)). Together, these methods create an approach to improve generalization across and within tasks. This motivation drove the adoption of meta-learning to optimize the sparsity-inducing hyperparameter rather than treating it simply as a learnable parameter within the MTL setting. The proposed approach in this work aims to meta-learn the sparsity hyperparameters (as well as the model parameters) across various combinations of multiple tasks, resulting in a sparse meta-learned backbone. Theoretically, as per meta-learning principles, the backbone should effectively adapt to previously unseen tasks.

This section provides a qualitative perspective on generalization grounded in an existing understanding of MTL, meta-learning, and structured sparsity. The aim of this sub-section is to interpret the empirical behavior of meta-sparsity and highlight how these components jointly support generalization across tasks, data, and features. Given the empirical-first nature of this work, this conceptual framing helps articulate the role of sparsity as a learned mechanism for selective feature sharing in multi-task contexts. A formal theoretical treatment, while valuable, would require a separate and dedicated framework that accounts for the complex interactions between bilevel optimization, structured sparsity, and task adaptation—elements that are beyond the current scope of this study.

Therefore, in the context of this work, generalization mainly refers to the adaptability of the shared backbone in a multi-task network, highlighting its capacity to generalize to previously unseen tasks and data. The robustness of the backbone lies in its ability to learn task-agnostic features that serve as a strong foundation for introducing new task-specific decoders during testing. Theoretically, this ensures that the shared backbone can adapt to previously unseen tasks, enabling efficient transfer of knowledge across tasks and encouraging scalability in multi-task settings. We demonstrate this empirically through the experimental results (in Section 5) by showing the capability of a backbone to support new tasks effectively, hence generalizing to new scenarios.

4 Experimental setup

In this section, we elaborate on the experimental framework designed to investigate the effectiveness of our proposed meta-sparse multi-task models. Here, we provide an overview of the datasets chosen for multi-task learning, describe the structure of the multi-task network used, and outline the specific evaluation metrics employed for each task. Additionally, we outline the types of experiments designed to assess the effectiveness of our proposed methodology.

Table 2: A table containing the loss functions and evaluation metrics for the various tasks for both the datasets: NYU-v2 and CelebAMask-HQ. In the table a downward arrow (↓) represents that a lower value is better while an upward arrow (↑) represents a higher value is better. Also, IoU stands for intersection over union and MAE stands for mean absolute error.

Dataset	Tasks	(T)	Loss Functions	Evaluation Metric
NYU-v2	Semantic segmentation	T_1	cross-entropy loss	IoU (↑)
	Depth estimation	T_2	Combination of errors in depth gradient and surface normal(Hu et al. (2019))	MAE (↓)
	Surface Normal estimation	T_3	Inverse cosine similarity	cosine similarity (↑)
	Edge detection	T_4	huber loss(Paul et al. (2022))	MAE (↓)
CelebA Mask-HQ	Semantic segmentation	T_1	cross-entropy loss	IoU (↑)
	Binary classification (attributes- male, smile, big lips, high cheekbones, wearing lipstick, bushy eyebrows)	$T_2 - T_7$	binary cross-entropy loss	Accuracy (↑)

In this work, two widely recognized and publicly accessible datasets, the NYU-v2 dataset (Nathan Silberman & Fergus (2012)) and CelebAMask-HQ dataset (Lee et al. (2020)), are used, hereafter referred to as NYU and CelebA, respectively in this paper. Table 2 details the various tasks considered for each dataset, the respective loss functions, and evaluation metrics (see Appendix or supplementary material for details). We have adopted the standard loss functions (and metrics) as utilized in previous works such as Sun et al. (2020b); Upadhyay et al. (2023a) and many others, to primarily focus on assessing the impact of sparsity on task performance and avoiding performance enhancements that could arise from the use of complex, custom-designed loss functions. Overall, in the NYU dataset, all the tasks are pixel-level tasks, segmentation is pixel-level classification, and the rest are pixel-level regression. While in the celebA dataset, there is only one pixel-level (classification) task, and the rest are image-level (classification) tasks. This set of tasks was chosen explicitly to extensively evaluate the performance of the proposed approach across a wide range of task combinations, proving their effectiveness and adaptability in many contexts.

As already discussed in Section 3, a very standard multi-task network architecture is chosen, which has a backbone network i.e., the layers shared by all the tasks, and task-specific heads or layers are connected to the output of the backbone, see Figure 2. We selected the dilated ResNet-50 (Yu et al. (2017)) architecture as our backbone network due to its resilience to sparsity; even when sparsity leads to entire layers having zero parameters, the residual connections within the network ensure continuity by effectively propagating values forward. This characteristic maintains the network's structural integrity and facilitates uninterrupted information flow, making it an ideal choice for our experiments. For the dense prediction tasks, a deeplab-v3 network (Chen et al. (2017)) is employed as a task-specific network, and for the binary classification task, a two-layer fully connected network is used. In the past, similar network designs and architecture were also used by Kendall et al. (2018); Liebel & Körner (2018); Upadhyay et al. (2023a), and many more. For a fair comparison of results and to maintain consistency across evaluations, all the experiments in this work use the same architecture, loss functions, metrics, train-validation-test split, and hyperparameters. Models are trained using NVIDIA A100 Tensor Core GPUs, which have 40 GB of onboard HBM2 VRAM. To assess the reliability of the model, we conducted five replications of each experiment using distinct random seeds. The findings are presented in terms of the mean and the standard deviation. To ensure reproducibility, the source code can be accessed at: https://github.com/PLACEHOLDER TO THE GIT REPOSITORY

The following are the types of experiments designed and analyzed in this work-

- Experiments *without* group sparsity (using the dense model, $\lambda = 0$)
  1. Single task learning - one model for each task.
  2. Multi-task learning - employ a multi-task model for different task combinations.
  3. Multi-task + meta-learning - learn the multi-task model parameter initialization only during meta-training.
     - These are also referred to as *meta-learning baseline* experiments in the subsequent text.
- Experiments *with* group sparsity (applying channel-wise structured sparsity on the backbone layers)
  1. Single task learning + sparse backbone; Fixed sparsity (i.e., λ is fixed).
  2. Multi-task learning + sparse backbone; Fixed sparsity (i.e., λ is fixed).
  3. Multi-task learning + meta-sparse backbone; Learnable sparsity (i.e., λ is meta-learned).
     - These are the *meta-sparsity* experiments designed to meta-learn both the parameter initialization and hyperparameter (λ) that induces sparsity.

In experiments involving meta-learning, namely the meta-learning baseline (MTL + meta-learning) and meta-sparsity (MTL + meta-learning + learnable sparsity), the performance of tasks under these three settings is evaluated during meta-testing, utilizing the backbone learned during meta-training:

1. Meta-testing on the same tasks as meta-training.
2. Add a new task, and fine-tune only the new task.
3. Add a new task to the meta-training task and fine-tune all the tasks.

To clarify, adding a new task involves integrating a new decoder to the meta-trained (multi-task) backbone for a task that has not been previously introduced i.e., during meta-training. Note that the single experiments without and with fixed sparsity do not use meta-learning for parameter initialization. Meta-learning is used in the MTL+ meta-learning (without sparsity) and meta-sparsity experiments. This means that the meta-parameter initializations obtained from meta-training are used during meta-testing for these experiments. Additionally, all the multi-task experiments are performed for 3-4 task combinations. Given the computation requirement, not all the $2^N - 1$ combinations for N tasks are evaluated. For the NYU dataset, we examine three multi-task scenarios: (i) the complete set (T_1, T_2, T_3, T_4) encompassing all tasks, (ii) a mixed set of classification and regression tasks (T_1, T_2, T_3) with one task reserved for meta-testing, and (iii) a subset of solely regression tasks (T_2, T_3, T_4), omitting the classification task for meta-testing purposes. Similarly, for the celebA dataset, the following combinations are considered : (i) all the seven tasks i.e., $(T_1 - T_7)$, (ii) all the binary classification tasks i.e., $(T_2 - T_7)$, and (iii) (T_1, T_2, T_3, T_7); other tasks with very similar attributes primarily related to the mouth region of the image were added during meta-testing to study the performance.

5 Results and Discussion

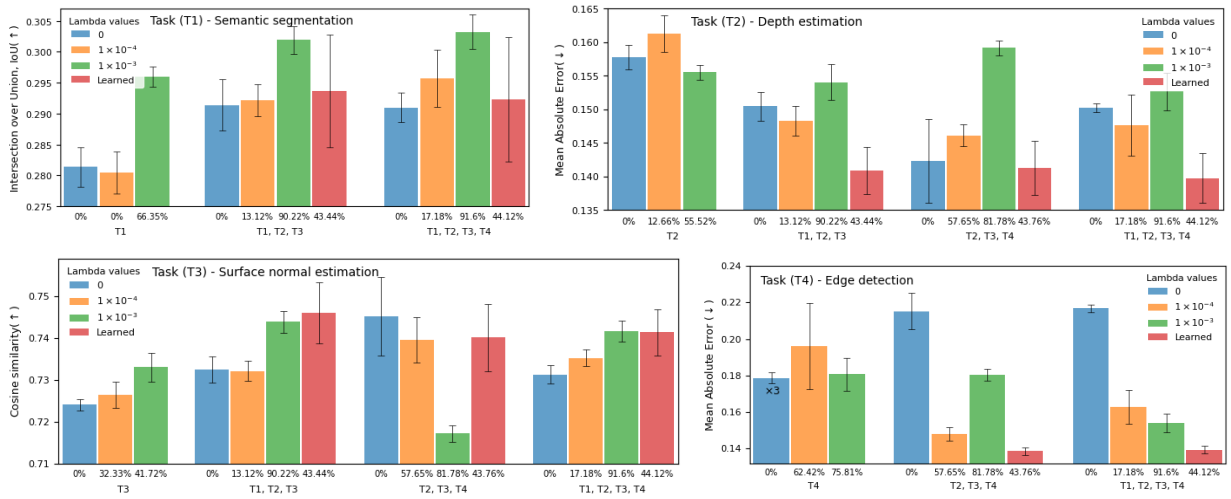


Figure 3: For NYU dataset, task-wise performance comparison of single-task and multi-task no sparse ($\lambda = 0$, in blue), fixed sparsity single and multi-task (for $\lambda = 1 \times 10^{-4}$ in yellow and $\lambda = 1 \times 10^{-3}$ in green) and meta sparsity ($\lambda =$ learned in red i.e., meta-sparsity) experiments. The vertical axis label is annotated with an upward or downward arrow to indicate whether a higher or lower metric value is preferable. The values below each bar represent the percentage of parameter sparsity in the backbone network. The 'x3' on the initial bar for task T4 indicates that the depicted performance metric (MAE) is triple the current value represented by the bar. This notation is employed to simplify the depiction of values that exhibit significant disparities. In these plots, we have selected a narrow range for the y-axis to make it easier to compare the performances. However, this may have enhanced the visual effect of the error bars representing the performance's standard deviation. These results are also presented in tabular form in the supplementary material Table A.1.

This section primarily answers the following questions: why multi-task over single-task learning? Is the meta-sparsity approach viable? Is the performance of meta-sparsity robust and stable? Do the observed improvements in meta-sparsity performance compared to the meta-learning baseline result from the effectiveness of meta-learning the sparsity hyperparameter, or are they merely a consequence of the advantages of meta-learning itself? How do the meta-sparse multi-task models perform compared to the fixed sparsity multi-task models? How effectively is the sparse backbone model processing a novel, unseen task? Therefore, this section aims to provide comprehensive insight into the applicability and advantages of the proposed meta-sparsity approach within MTL learning, supported by empirical evidence. Detailed results are provided in the Appendix for further reference.

Note: For the fixed lambda experiments, we looked at how different tasks and combinations of tasks respond to the same setting of a sparsity parameter, λ. This parameter controls the level or amount of sparsity, which is measured in terms of (%) parameter sparsity[4]. We focused on three specific settings of this parameter: 1×10^{-3}, 1×10^{-4}, and 1×10^{-5} because these values induced sparsity in most of the single-task and multi-task settings.

Assessing the viability of meta-sparsity: Figures 3 and 4 illustrate the task-wise performance for the NYU and celebA datasets, respectively. For ease of comparison, the bar charts display the results for single-task learning (both with and without fixed sparsity), multi-task learning (again, with and without fixed sparsity), and meta-sparsity multi-task learning (featuring learned sparsity) across all tasks. For the NYU dataset (Figure 3), for tasks T_2 and T_4, the meta-sparse multi-task models significantly outperform compared to other model configurations. For task T_3, these models achieve performance on par with their counterparts, whereas for task T_1, they slightly under-perform relative to the single or multi-task fixed sparsity counterparts, while are equivalent or better than not sparse models. Meta-sparse models surpass

[4]In this work, *parameter sparsity* refers to the proportion of the model's parameters which are zeroed out, represented as a percentage

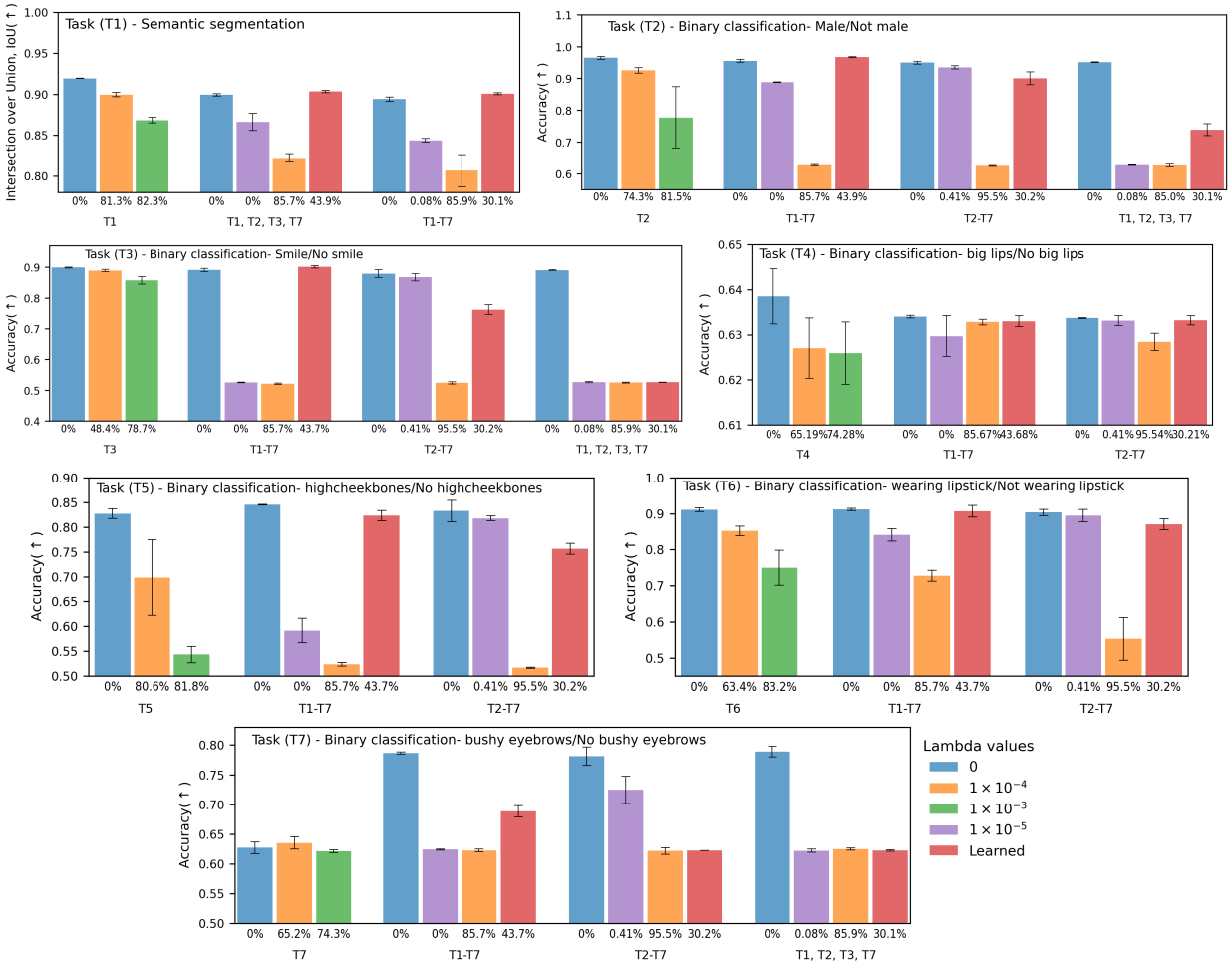


Figure 4: For celebA dataset, task-wise performance comparison of single-task and multi-task no sparse ($\lambda = 0$, in blue), fixed sparsity single and multi-task (for $\lambda = 1 \times 10^{-5}$ in lavender, $\lambda = 1 \times 10^{-4}$ in yellow and $\lambda = 1 \times 10^{-3}$ in green) and meta sparsity (in red) experiments. The vertical axis label is annotated with an upward or downward arrow to indicate whether a higher or lower metric value is preferable. These results are also presented in tabular form in the supplementary material Table A.3.

their fixed-sparsity counterparts in terms of performance despite having a lower level of parameter sparsity, highlighting a trade-off between performance and sparsity.

For the celebA dataset, meta-sparsity excels for some task combinations. However, specifically for the task combination $T1, T_2, T_3, T_7$, the performance across all the tasks, except for T_1 (i.e., segmentation), is undesirable. A probable reason behind this can be that the task ensemble involves classification tasks aimed at significantly distinct attributes. This under-performance can primarily be attributed to task interference, where the meta-sparsity approach faces challenges in identifying optimal features for sharing between tasks. However, the expanded combination of $T_1 - T_7$ leads to improved performance for many of these tasks. This improvement suggests that more related (similar attributes) tasks improve performance through enhanced feature sharing among tasks facilitated by meta-sparsity. Some exceptions are discussed further in this section.

Regularization Stochasticity and discussion on performance stability: To enhance the visibility and comparability of the performance differences, we chose a narrow y-axis range for the plots in Figure 3, which may have amplified the visual impact of the variability of the error bars representing the standard deviation. Please refer to Table A.1 in the supplementary material (which forms the basis of Figure 3), which quantitatively demonstrates that the standard deviations of the performance metrics of the tasks are

consistently low (in the range of 0.001-0.0101). However, it is evident that for many tasks, the variance in the performance of meta-sparsity is slightly greater than the rest (no sparsity and fixed sparsity). One probable reason can be 'Regularization Stochasticity' (Sandjakoska & Bogdanova (2018)). It can be defined as the variability in the learned sparsity patterns because of the stochastic nature of (mini-batch) gradient-based optimization and the dynamic penalty-based sparsity applied during training. This stochasticity can result in different paths of convergence and patterns of sparsity when the same experiment is run multiple times; therefore, there is slight variability in the performance. Another factor to consider, that can amplify these stochastic effects, is the random initialization of the strength of the regularization hyperparameter (λ), which is trainable/learned in meta-sparsity. We sample the initial value of λ from a uniform distribution between 0.1 and 1. While this may seem like a small range, it can still lead to significant variations in the convergence paths and the resulting sparsity patterns. The aforementioned reasons for performance instability are also applicable to the CelebA dataset.

Stability in the amount (%) of sparsity with fixed λ and in meta-sparsity: As the preceding subsection addresses performance stability, it is also essential to look at the stability of percentage sparsity over the experiments. Table A.1 in the supplementary material presents the percentages of group sparsity and parameter sparsity for the NYU-v2 dataset, while task performance is also illustrated in Figure 3. In both single-task and multi-task experimental settings, under fixed sparsity, the percentage of group and parameter sparsity exhibits significant variance (high standard deviation) across multiple trials. The high variance comes from differences in parameter initialization, causing small differences in the trained parameters (regularization stochasticity as discussed above). These small changes can disproportionately impact sparsity by leading to the elimination of entire groups or channels of the parameter matrices, resulting in considerable fluctuations in overall sparsity levels. In contrast, the meta-sparsity experiments demonstrate substantially lower variance in percentage sparsity, highlighting the robustness of the proposed approach. This behavior can be observed for both datasets (see Tables A.1 and A.3 in the supplementary material). The NYU dataset exhibits greater variability in the percentage sparsity of the meta-sparsity experiments compared to the CelebA dataset. This is because NYU tasks involve dense, pixel-level predictions, which demand diverse and task-specific adjustments to the sparsity patterns across different layers of the shared network to preserve important features. In contrast, the classification tasks of the celebA dataset share more uniform feature extraction needs, resulting in comparatively more consistent sparsity levels during meta-training.

Comparative performance analysis: Before evaluating the proposed meta-sparsity approach, we would like to provide an insight into why MTL is preferred over single-task learning. Experiments (Figures 3 and 4) typically show that tasks perform better in a multi-task environment compared to a single-task environment. This observation emphasizes the importance of utilizing multi-task learning episodes. Additionally, the amount of sparsity varies depending on the specific task (in single-task scenarios) and the combination of tasks (in multi-task scenarios). There is no clear trend in sparsity levels that might help to predict how the sparsity of a multi-task model changes in relation to the number of tasks. It can be inferred that sparsity is affected by the nature and interconnection of the tasks involved. Further elaboration on task performance in the celebA dataset is provided in the following subsections.

Interestingly, when analyzing the outcomes for the celebA dataset, we noticed that for the lowest value i.e., 1×10^{-5}, the experiments, both single and multi-task, show no sparsity at all, and the performance is also similar to the without sparsity setting. While for 1×10^{-3} and 1×10^{-4}, they exhibit very high sparsity (around 85% - 95%) in just one or two epochs, but this comes at the cost of not being trained enough, which negatively affects its performance (not for single tasks). This is the reason behind the poor performance of all the tasks for $\lambda = 1 \times 10^{-3}$ and 1×10^{-4}, see the Figure 4 (the lavender and yellow bars). In the case of single-task experiments, they perform better since the feature requirement in single-task settings is much simpler (straightforward) than in multi-task settings. From the above analysis, it is logical to infer that other values of λ, both lower than 1×10^{-5} and higher than 1×10^{-3}, would exhibit similar behaviors. Specifically, values below 1×10^{-5} may not cause considerable sparsity, potentially resulting in overfit models without performance advantages, while values above 1×10^{-3} may result in sparse models early in training, impeding learning and performance. This conjecture highlights the delicate balance needed to optimize sparsity and model performance when selecting λ. This fuels the rationale behind the primary aim of this research, which is to learn the optimal sparsity parameter λ, which in turn is expected to enhance performance.

Table 3: Performance comparison between the proposed meta-sparsity approach (with meta-learnable λ) and a conventional meta-learning baseline that only learns parameter initialization in an MTL setting, evaluated on the NYU dataset. The baseline incorporates both multi-task and meta-learning approaches while omitting sparsification. This table compares the performance of the tasks for NYU dataset when a new unseen task is added during the meta-testing stage. The new tasks are highlighted in blue, and the best (mean value) metrics for each task are in bold.

Meta-training	**Meta-testing**	**Segmentation** T_1 IoU(↑)	**Depth est.** T_2 MAE(↓)	**SN est.** T_3 CS(↑)	**Edge det.** T_4 MAE(↓)	**Parameter sparsity (%)**
MTL + meta-learning (without any sparsity in the shared backbone, $\lambda = 0$)						
T_1,T_2,T_3	T_1,T_2,T_3	0.2750 ± 0.0109	0.1449 ± 0.0006	0.7263 ± 0.0009		0
T_2,T_3,T_4	T_2,T_3,T_4		0.1563 ± 0.0048	0.7278 ± 0.0018	0.1414 ± 0.0037	0
T_1,T_2,T_3,T_4	T_1,T_2,T_3,T_4	0.2769 ± 0.0039	0.1476 ± 0.0050	0.7235 ± 0.0017	0.1441 ± 0.0030	0
Adding unseen tasks during meta-testing in **MTL+meta-learning**						
T_1,T_2,T_3	T_1,T_2,T_3,+T_4	0.2796 ± 0.0053	0.1467 ± 0.0033	0.7257 ± 0.0050	**0.1380 ± 0.0009**	0
T_1,T_2,T_3	finetuning only T_4	-	-	-	0.1541 ± 0.0028	0
T_2,T_3,T_4	T_2,T_3,T_4,+T_1	0.2704 ± 0.0064	0.1497 ± 0.0059	0.7237 ± 0.0048	0.1428 ± 0.0024	0
T_2,T_3,T_4	finetuning only T_1	0.2619 ± 0.0038	-	-	-	0
Meta-Sparsity (MTL+ meta-learning + group sparsity, λ = meta-learnable)						
T_1,T_2,T_3	T_1,T_2,T_3	0.2937 ± 0.0091	0.1409 ± 0.0035	**0.7460 ± 0.0073**		43.4391 ± 0.1925
T_2,T_3,T_4	T_2,T_3,T_4		0.1412 ± 0.0040	0.7402 ± 0.0080	0.1386 ± 0.0019	43.7577 ± 0.1886
T_1,T_2,T_3,T_4	T_1,T_2,T_3,T_4	0.2923 ± 0.0101	0.1397 ± 0.0037	0.7414 ± 0.0055	0.1395 ± 0.0021	44.1159 ± 0.3696
Adding unseen tasks during meta-testing in **Meta-Sparsity**						
T_1,T_2,T_3	T_1,T_2,T_3,+T_4	**0.3003 ± 0.0067**	0.1389 ± 0.0030	0.7438 ± 0.0005	0.1404 ± 0.0015	43.4391 ± 0.1925
T_1,T_2,T_3	finetuning only T_4	-	-	-	0.1431 ± 0.0020	43.4391 ± 0.1925
T_2,T_3,T_4	T_2,T_3,T_4,+T_1	0.2950 ± 0.0069	**0.1378 ± 0.0020**	0.7444 ± 0.0017	0.1386 ± 0.0003	43.7577 ± 0.1886
T_2,T_3,T_4	finetuning only T_1	0.2828 ± 0.0392	-	-	-	43.7577 ± 0.1886

Also, for the task T_7 i.e., bushy eyebrows/ no bushy eyebrows, the performance of meta sparsity is not up to the mark for any of the task combinations. This shortfall could be attributed to the unique nature of the task. Most selected tasks are associated with attributes of the entire image, such as segmentation and gender classification, or specifically relate to the mouth area, including distinctions like smiling/not smiling, having big lips/no big lips, and wearing lipstick/not wearing lipstick; the sparse features dominate towards these tasks. In contrast, task T_7 is the only task that concentrates on the eye region, specifically eyebrows, which likely requires features different from those needed for the other tasks, which is why its performance in isolation is much better. Similarly, the semantic segmentation task T_1 from the NYU dataset performs satisfactorily in a fixed-sparsity situation but does not reach comparable performance levels under meta-sparsity (although there is a significant standard deviation). This discrepancy is likely due to the nature of T_1 as the sole pixel-level classification task among others that are pixel-level regression tasks, suggesting that sparse meta-parameters might not be well-suited to support T_1 effectively. Overall, it can be summarized that the relatedness of the tasks influences their feature requirements, which in turn dictates both the sparsity pattern and performance outcomes. The competitive and cooperative dynamics of MTL might cause some tasks to struggle or perform poorly in the ensemble while others may excel. It emphasizes the significance of cautiously choosing and balancing tasks in an ensemble to enhance overall performance and sparsity efficiency.

Comparing meta-sparsity and MTL + meta-learning (meta-learning baseline): Tables 3 and 4 offer a comparison between the proposed meta-sparsity approach and a baseline meta-learning method without sparsification in a MTL setup. The proposed meta-sparsity approach performs better than the conventional meta-learning baseline across almost all evaluated tasks for both datasets. It is important to observe that the performance metrics of single-task and standard multi-task experiments frequently match closely with the meta-learning baseline. The performance of the baseline meta-learning approach may, in certain instances, be marginally inferior to that of standard MTL (without sparsity). This suggests meta-learning gains may not always translate into large improvements across all tasks. It might be because a meta-learning approach that focuses on optimizing for a shared initialization across tasks may face difficulties in sufficiently capturing the distinct features of individual tasks, particularly when tasks are diverse. The performance gains in

Table 4: Performance comparison between the proposed meta-sparsity approach (with meta-learnable λ) and a conventional meta-learning baseline that only learns parameter initialization in an MTL setting, evaluated on the celebA dataset. The baseline incorporates both multi-task and meta-learning approaches while omitting sparsification. This table compares the performance of the tasks for celebA dataset when a new unseen task is added during the meta-testing stage. The new tasks are highlighted in blue, and the best (mean value) metrics for each task are in bold.

Meta-training	**Meta-testing**	**Segmentation** T_1 IoU(↑)	**male** T_2 Accuracy(↑)	**smile** T_3 Accuracy(↑)	**biglips** T_4 Accuracy(↑)	**highcheek bones** T_5 Accuracy(↑)	**wearing lipstick** T_6 Accuracy(↑)	**bushy eyebrows** T_7 Accuracy(↑)	**Parameter sparsity** (%)
MTL + meta-learning (without any sparsity in the shared backbone, $\lambda = 0$)									
T_1-T_7	T_1-T_7	0.8922±0.0067	0.8467±0.0108	0.6446±0.0021	0.6010±0.0013	0.6272±0.0018	0.9138±0.0020	0.5993±0.0510	0
T_2-T_7	T_2-T_7		0.6297±0.0100	0.5071±0.0022	0.5993±0.0012	0.5221±0.0010	0.7560±0.0078	0.6053±0.0480	0
T_1,T_2,T_3,T_7	T_1,T_2,T_3,T_7	0.8942±0.0010	0.6297±0.0100	0.5261±0.0030				0.6103±0.0501	0
Adding unseen tasks during meta-testing in **MTL+meta-learning**									
T_2-T_7	T_2-T_7, +T_1	0.8731±0.0159	0.9479±0.0136	0.5261±0.0024	0.6140±0.0014	0.5905±0.0118	0.9127±0.0080	0.6223±0.0173	0
T_2-T_7	finetune only T_1	0.8913±0.0015	-	-	-	-	-	-	0
T_1,T_2,T_3,T_7	T_1,T_2,T_3,T_7, + T_4,T_5,T_6	0.8944±0.0022	0.9494±0.0257	0.5261±0.0016	**0.6340±0.0031**	0.5221±0.0095	**0.9205±0.0098**	0.6223±0.0105	0
T_1,T_2,T_3,T_7	finetune only T_4,T_5,T_6	-	-	-	0.6290±0.0021	0.5221±0.0015	0.7620±0.0306	-	0
Meta-Sparsity (MTL+ meta-learning + group sparsity)									
T_1-T_7	T_1-T_7	0.9007±0.0012	**0.9669±0.0014**	**0.9014±0.0043**	0.6330±0.1680	0.8235±0.0104	0.9068±0.0165	0.6885±0.0936	43.6893±0.3593
T_2-T_7	T_2-T_7		0.9004±0.0203	0.7618±0.1602	0.6330±0.0720	0.7562±0.1109	0.8703±0.0154	0.6223±0.0002	30.2145±0.0016
T_1,T_2,T_3,T_7	T_1,T_2,T_3,T_7	**0.9034±0.0013**	0.7386±0.0188	0.5261±0.0010				0.6223±0.0010	30.0187±0.0011
Adding unseen tasks during meta-testing in **Meta-Sparsity**									
T_2-T_7	T_2-T_7, +T_1	0.8985±0.0027	0.9615±0.0051	0.8977±0.0072	0.6330±0.0091	**0.8278±0.0057**	0.9102±0.0144	**0.7529±0.0199**	30.2145±0.0016
T_2-T_7	finetune only T_1	0.9033±0.0019	-	-	-	-	-	-	30.2145±0.0016
T_1,T_2,T_3,T_7	T_1,T_2,T_3,T_7, + T_4,T_5,T_6	0.9019±0.0005	0.9559±0.0191	0.8995±0.0116	0.6330±0.0130	0.8206±0.0066	0.9073±0.0070	0.7250±0.0890	30.0187±0.0011
T_1,T_2,T_3,T_7	finetune only T_4,T_5,T_6	-	-	-	0.6330±0.0011	0.7373±0.0117	0.8812±0.0096	-	30.0187±0.0011

meta-sparsity can be noticed when introducing unseen tasks during the meta-testing stage and fine-tuning only the new tasks. Further details on this comparison are provided in the next sub-section, while this section focuses specifically on comparison with the meta-learning baseline. In the meta-learning baseline experiments involving the addition of unseen tasks, the meta-model adapts to these additional tasks, resulting in performance levels comparable to that observed in single-task and multi-task configurations. However, there is no significant improvement in performance, except for a few tasks within the celebA dataset.

As stated, meta-learning aims to find an optimal parameter initialization that shows good generalization across various tasks. In the MTL setting, it is worth noticing that parameter initialization alone may not be sufficient for effectively learning various tasks. This shared initialization lacks inherent specialization for capturing the distinct and refined features of individual tasks. This limitation affects its ability to generalize, particularly in the context of unseen tasks. Overall, the results show that integrating group sparsity into the meta-learning + MTL framework (i.e., resulting in meta-sparsity) improves the overall performance and boosts the generalizability of the learned shared representations. This is mainly because group sparsity, by reducing redundant parameters, forces the model to focus on features beneficial for both shared learning and individual task performance, thereby enhancing the adaptability of the model. Hence, the interaction of MTL, meta-learning, and group sparsity (in meta-sparsity) can generalize better, adapt more efficiently to new tasks, and deliver higher performance compared to the meta-learning baseline that lacks sparsity, thereby validating the hypothesis presented in Section 3.

Evaluating the efficacy of meta-sparse backbone: We study the effectiveness of the sparse backbone by introducing novel, previously unseen tasks during the meta-testing stage, i.e., a task different from the ones the model is meta-trained on. So, both the task and the data during meta-testing are unseen. We studied the performance of the sparse shared backbone network under two distinct scenarios: firstly, when the new task is integrated alongside the tasks from the meta-training phase, and secondly, when the model is fine-tuned exclusively on the new task. Note that the level of sparsity achieved during the meta-training stage is maintained during meta-testing by masking the layers that were zeroed out. Tables 4 and 3 show the

performance of the new tasks for the celebA and NYU datasets, respectively. For comparison, we also show the performance of the meta-trained tasks during meta-testing.

For the celebA dataset, when tasks T_4, T_5, T_6 are added to the pre-existing set of tasks T_1, T_2, T_3, T_7 for meta-testing, the performance across the tasks improves or remains stable, without any significant degradation. Notably, task T_3 (smile classification) shows significant improvement with the inclusion of mouth-related tasks T_4 (big lips/no-big lips) and T_6 (wearing lipstick/not wearing lipstick) due to more focused learning on mouth features. Similarly, tasks T_2 (male classification) and T_7 (bushy eyebrows classification) benefit from this refined feature extraction, enhancing performance. Similar observations can be made when semantic segmentation T_1 (i.e., a pixel-level task) is added to the mix of classification tasks ($T_2 - T_7$). The segmentation task demands pixel-level, fine-grained image understanding, which enhances the shared feature representation, benefiting the classification tasks with more robust and discriminative features. For the NYU dataset (see Table 3), in both the cases, i.e., addition of T_1 and T_4, the performances of the tasks are consistent when compared to the outcomes of other settings. When these tasks are fine-tuned in a multi-task setting along with other tasks, there is either slight improvement or maintenance of performance levels for the existing tasks without any observed degradation.

These observations highlight the advantages of MTL, where simultaneous training on multiple tasks can lead to better overall performance through shared insights and learning dynamics. It also highlights the performance consistency across tasks, i.e., the sparse backbone demonstrates robust behavior even when new tasks are introduced in the mix. Occasionally, it is noticed that the addition of new tasks might also enhance the performance of meta-training (old) tasks. This suggests that the tasks mutually support and improve learning. Furthermore, the fact that meta-training tasks maintain stable performance during meta-testing, even with the introduction of new tasks, suggests that the proposed method is robust and may help prevent negative information transfer.

Comparisons with other sparsity baselines: To give a baseline performance comparison of the proposed meta-sparsity approach with other sparsification methods, Table 5 presents a comparison in three levels: (i) Sparsification approaches illustrated in Figure 1, (ii) Sparsity patterns are also referred to as masks in this discussion, and (iii) Parameter initialization before sparsification. For a fair comparison between the approaches, we forced all the sparsification methods to maintain the same % parameter sparsity achieved by meta-sparsity. From Table 5 it is evident that there is no one approach which works the best for all the tasks. The lowest magnitude parameter elimination for progressive and iterative sparsification shows promising results for T_1, T_2, T_3, but for T_4 the performance is suboptimal. Zeroing out the parameters randomly also shows some promising performance. However, it is to be noted that these performances are at an optimal sparsity budget($\sim$44%) learned by meta-sparsity. As the above table shows, meta-sparsity achieves comparable performance across all tasks. The strength of our approach lies in its ability to dynamically (meta-) learn sparsity patterns, which leads to an optimal amount of sparsity. In contrast, other methods require setting sparsity budgets, thresholds, or step sizes (in iterative/progressive pruning) to regulate the sparsity level. Finding the right balance between compression and performance can be tedious and non-trivial. To verify the viability of the learned meta-sparsity patterns, we applied the learned meta-mask across various sparsification approaches. The meta mask/pattern consistently performed well for almost all tasks and across all approaches, demonstrating that the learned pattern is an optimal sparsity pattern for various tasks in an MTL setting.

In addition to the performance comparison, Table 6 presents a detailed analysis of training time and tuning complexity for each approach. While meta-sparsity includes the overhead of meta-learning, baseline methods like iterative and progressive sparsification require extensive hyperparameter tuning—such as selecting step sizes, pruning thresholds, and fine-tuning epochs, which significantly increase total training time. As shown in Table 6, the total training time for iterative and progressive sparsification is comparable to or even greater than meta-sparsity when hyperparameter tuning is taken into account. As already mentioned, all approaches were evaluated under the same final sparsity level (44%) to ensure a fair comparison. On the other hand, approaches like one-shot pruning and sparse training report significantly lower training times. This is expected, as they involve minimal or no iterative tuning. In these methods, the only tunable parameter is the pruning ratio, which we fixed to match the final sparsity level achieved by meta-sparsity (44%) for fair comparison. However, it is important to note that these methods rely on static, manually specified sparsity patterns (e.g.,

Table 5: Performance analysis of the sparsification approaches presented in Figure 1, for the NYU-v2 datset.

Sparsification approaches	**Sparsity patterns**	**parameter init. before sparsification**	**Segmentation** T_1 **IoU(↑)**	**Depth est.** T_2 **MAE(↓)**	**SN est.** T_3 **CS(↑)**	**Edge det.** T_4 **MAE(↓)**
One-shot	Mask-1, magnitude	MTL dense	0.2345 ± 0.0008	0.1777 ± 0.0097	0.6601 ± 0.0250	0.3069 ± 0.0325
	Mask-3, random	MTL dense	0.3185 ± 0.0010	0.1337 ± 0.0018	0.7412 ± 0.0027	**0.1318 ± 0.0026**
	Meta mask	MTL dense	0.2308 ± 0.0106	0.1682 ± 0.0065	0.6897 ± 0.0062	0.3036 ± 0.0214
Iterative	Mask-2, iterative magnitude	MTL dense	0.3082 ± 0.0094	0.1367 ± 0.0014	0.7346 ± 0.0043	0.1353 ± 0.0008
	Meta mask	MTL dense	0.3008 ± 0.0080	0.1373 ± 0.0007	0.7314 ± 0.0027	0.1356 ± 0.0008
Progressive	Mask-2, iterative magnitude	random	0.3855 ± 0.0139	0.1491 ± 0.0209	0.7800 ± 0.0102	0.1957 ± 0.0161
	Mask-3, random	random	0.3740 ± 0.0155	0.1361 ± 0.0040	0.7772 ± 0.0079	0.2176 ± 0.0228
	Meta mask	random	**0.4018 ± 0.0082**	0.1391 ± 0.0007	**0.7877 ± 0.0060**	0.1978 ± 0.0017
Sparse training	Mask-1 , magnitude	random	0.2918 ± 0.0112	0.1488 ± 0.0049	0.7202 ± 0.0058	0.2289 ± 0.0035
	Mask-3, random	random	0.2959 ± 0.0077	0.1530 ± 0.0009	0.7180 ± 0.0033	0.2389 ± 0.0105
	Meta mask	random	0.3906 ± 0.0087	**0.1282 ± 0.0050**	0.7827 ± 0.0022	0.2001 ± 0.0102
Meta-sparsity	Meta-mask/pattern	random	0.2923 ± 0.0101	0.1397 ± 0.0037	0.7414 ± 0.0055	0.1395 ± 0.0021

Note: Mask-1, one-shot sparsification by eliminating the lowest magnitude weights(Janowsky (1989)).
Mask-2, iterative magnitude sparsification by eliminating the lowest magnitude weights in steps.
Mask-3, random sparsification.
Meta-mask is the optimal sparsity pattern/mask learned by the meta-sparsity experiment.
The % parameter sparsity is kept constant across all the experiments, equal to the meta-sparsity achieved, i.e.,∼44.11%.

Table 6: Computation (training) time comparison across different sparsification baseline approaches presented in Figure 1. The time is averaged over five trials.

Sparsification approaches	**Sparsity pattern**	**Tuned hyperparameter**	**Range of hyper-parameter**	**Training time (in hours)**
One-shot	Mask 1, magnitude	Sparsification threshold	Fixed$_{(\sim 44\%)}$	5.2
	Mask 3, random	Sparsification threshold	Fixed$_{(\sim 44\%)}$	5.2
Iterative	Mask 2, iterative magnitude	Pruning ratio (per step)	1%-10%	21.87
Progressive	Mask 2, iterative magnitude	Pruning ratio (per step)	1%-10%	20.5
	Mask 3, random	Pruning ratio (per step)	1%-10%	21.67
Sparse training	Mask 1, magnitude	Sparsification threshold	Fixed$_{(\sim 44\%)}$	2.68
	Mask 3, random	Sparsification threshold	Fixed$_{(\sim 44\%)}$	2.68
Meta-sparsity	Meta-mask	Sparsification hyperparameter λ	learnable	19.56

Note: In one-shot and sparse training, the only hyperparameter in the approach is fixed as per meta-sparsity. Therefore, there was no hyperparameter tuning for these methods.
Sparsification threshold- A predefined value used to determine which model parameters are pruned either based on their magnitude or through random selection.
Pruning ratio (per step)- A fixed percentage of parameters pruned in each iteration, typically based on magnitude or random selection, and applied progressively over training.

pruning by magnitude or random selection) that are not adapted to task performance or data characteristics. As a result, while they are faster to execute, their performance is often less reliable and highly sensitive to the chosen pruning ratio. Moreover, they do not offer the flexibility or generalization capability of meta-sparsity.

While we acknowledge the importance of computational efficiency, it is also important to emphasize that these sparsification methods are fundamentally different in nature. Traditional baseline methods apply post-hoc heuristics, such as magnitude-based pruning or random pruning. In contrast, meta-sparsity integrates sparsification directly into the training process, where both the model parameters and the sparsity pattern are learned jointly through optimization, and sparsity is dynamically induced while training. Because of these methodological differences between manual pruning and learned regularization, a direct comparison based solely on runtime may not fully reflect the value of each approach. Instead, we argue that performance under a fixed sparsity constraint is a more appropriate and meaningful basis for comparison, especially in multi-task and heterogeneous-task settings where adaptability matters. We also acknowledge that meta-learning is inherently more computationally demanding than simple pruning. However, the benefits it offers, such as fast

adaptation to new tasks, the ability to handle heterogeneous tasks, and the learning of optimal structured sparsity patterns, justify this additional cost.

Other sparsity metrics: In the context of sparse models, compression ratio[5] (CR) and speed-up[6] (Sp) are two important metrics that quantify the application of sparsity(Blalock et al. (2020)). The compression ratio measures the extent of model compression by comparing the size (in a number of parameters) of the original model with the compressed model. Speed-up is not a direct measure of the size reduction; it is a result of model compression. Due to sparsity, when a model is compressed, it typically requires fewer computational resources i.e., FLOPs, which can lead to faster processing times. Therefore, speed-up is an indirect measure of the operational efficiency of a model achieved due to model compression.

Figure 5 shows the task-wise compression ratio and speed-up achieved due to the fixed sparsity and meta sparsity for different task combinations. The meta-sparsity metrics are circled in red. Except for task T_1 (segmentation), these figures illustrate a trade-off between performance and both compression and speed. This observation aligns with our earlier discussion on parameter sparsity vs performance in the comparative performance analysis subsection. For example, in task T_2 (depth estimation), models with meta-sparsity achieve a computation speed of approximately 1.6× faster than those of the dense backbone network. While fixed-sparsity models may be faster and more compressed than their meta-sparsity counterparts, this advantage often results in a trade-off with performance. For the segmentation task, it is apparent that meta-sparsity fails to boost performance and does not meet the anticipated outcomes. While the fixed sparsity models achieve notably greater compression, they can increase their speed by fourfold and exceed expected performance levels.

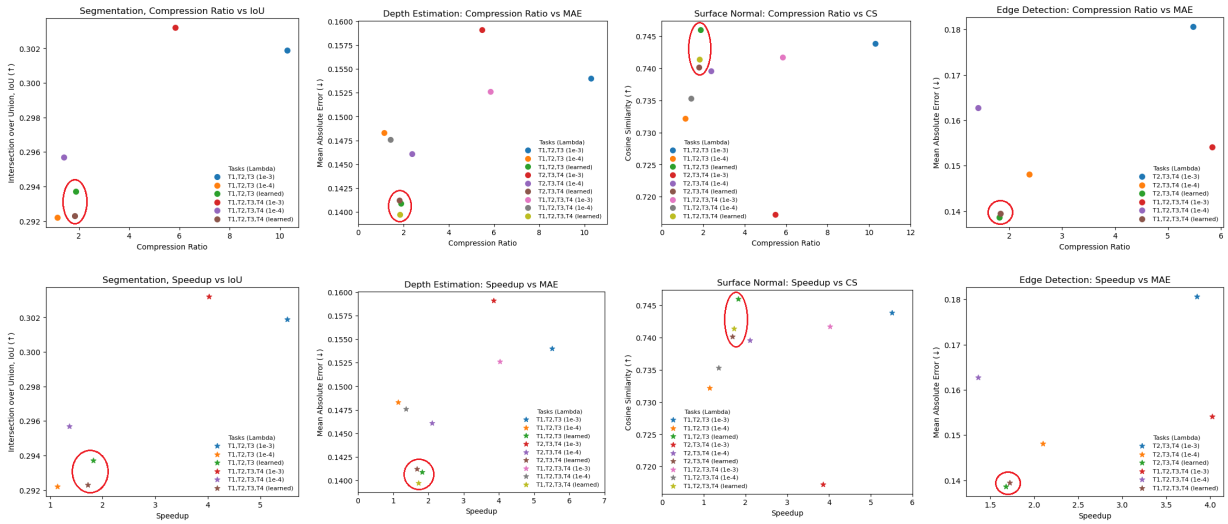
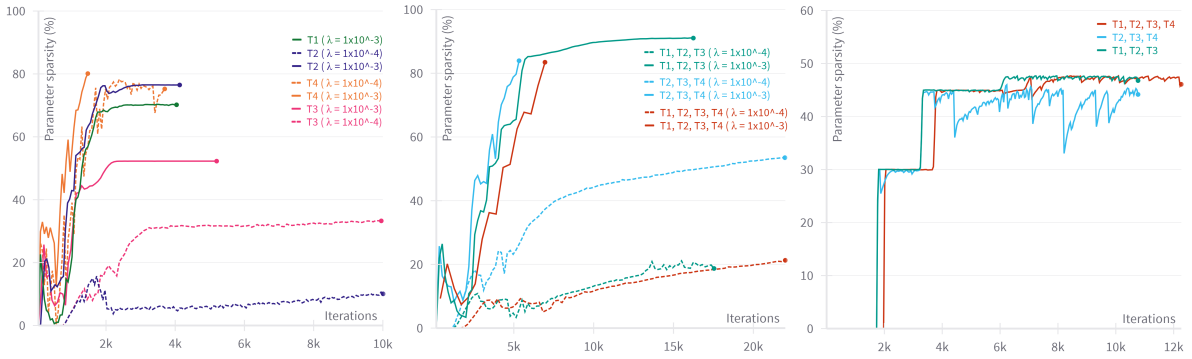


Figure 5: This figure presents a comparison of performance against both the compression ratio (top row) and speed-up (bottom row) across all tasks within the NYU dataset, with meta-sparsity experiments distinctly marked by red circles. It is important to note that the upward arrow (↑) on the y-axis denotes that a higher value of the metric is preferable, and the downward arrow (↓) represents that a lower value of the metric is preferable. The tabulated metrics are presented in Table A.4 in the supplementary material.

Sparsity profiles: Sparsity profiles illustrate the dynamic changes in the proportion of zero or inactive parameters within a model during the training process, effectively mapping the evolution of model compactness. Figure 6 illustrates the parameter sparsity profiles for the fixed and meta-sparsity experiments during training. It is evident from Figure 6(a) and 6(b) that sparsity increases sharply early in training and then plateaus, suggesting that sparsity is introduced quickly and maintained throughout the training process. The

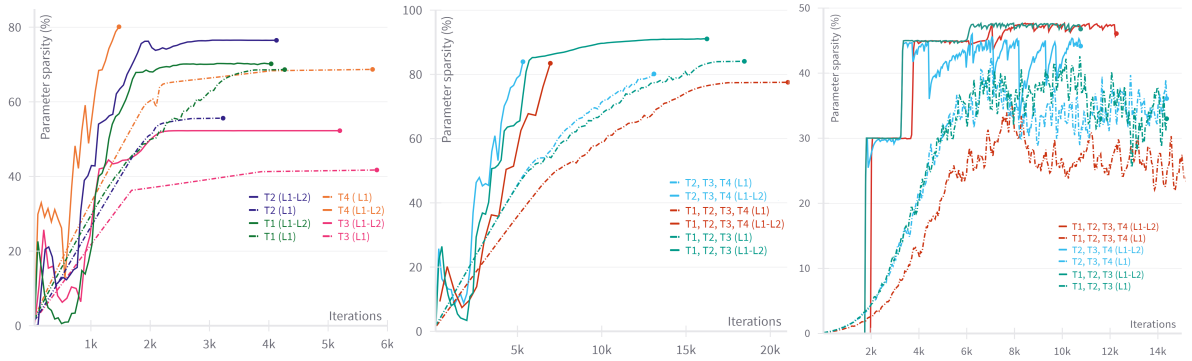
[5] $CR = \dfrac{total\ parameters}{no.\ of\ nonzero\ parameters}$

[6] $Sp = \dfrac{total\ FLOPs}{no.\ of\ nonzero\ FLOPs}$; FLOPs = floating point operations



(a) single-task fixed sparsity (b) multi-task fixed sparsity (c) multi-task meta sparsity

Figure 6: Parameter sparsity patterns while training for (a) single-task fixed sparsity, (b) multi-task fixed sparsity, and (c) multi-task meta sparsity experiments. In the above plots, T1 represents semantic segmentation, T2 represents depth estimation, T3 represents surface normal estimation, and T4 represents edge detection tasks. In the fixed sparsity plots i.e., (a) and (b), the dotted lines represent the experiments where $\lambda = 1 \times 10^{-4}$, while the solid lines represent the sparsity pattern when $\lambda = 1 \times 10^{-3}$.



(a) single-task fixed sparsity (b) multi-task fixed sparsity (c) multi-task meta sparsity

Figure 7: Parameter sparsity patterns for structured ($l_1 - l_2$ channel-wise group sparsity, solid lines) and unstructured sparsity (fine-grained l_1 sparsity, '__' lines) while training for (a) single-task fixed sparsity, (b) multi-task fixed sparsity, and (c) multi-task meta sparsity experiments. In the above plots, T1 represents semantic segmentation, T2 represents depth estimation, T3 represents surface normal estimation, and T4 represents edge detection tasks for the NYU dataset.

experiments with $\lambda = 1 \times 10^{-4}$ attain lower levels of parameter sparsity as compared to the $\lambda = 1 \times 10^{-3}$; this is obvious since λ defines the strength of sparsity. Moreover, sparsity is achieved more swiftly in single-task setups than in multi-task ones. This is because MTL needs more iterations to determine which features are unnecessary for the ensemble and may be removed.

In Figure 6(c), which shows the sparsity profile for meta-sparsity settings, the sparsity levels appear more stable and less variable over iterations than fixed sparsity settings. The lines are relatively flat, indicating that once the sparsity level is set, it doesn't change much during the training for a very long time. This could suggest that meta-sparsity leads to a more consistent sparsity pattern, resulting in the consistent performance of the sparse model. A stable sparsity pattern may indicate that the model has learned a general representation that is not overly fitted to the noise or eccentricity of the training data, which can lead to better generalization on unseen data (or tasks).

Structured vs unstructured sparsity: In this work, we have focused on meta-sparsity within the context of a group (channel-wise) or structured sparsity. We propose that meta-sparsity is a versatile concept, extendable to various forms of sparsity—be it structured, unstructured, penalty-driven, or any other pruning

methods controlled by hyperparameters (denoted by λ in this case). To support our claim, we extended the use of meta-sparsity to include fine-grained l_1 (unstructured) sparsity under various experimental scenarios: single-task fixed sparsity, multi-task fixed sparsity, and multi-task meta-sparsity.

Figure 7 shows the sparsity profile under $l_1 - l_2$ and l_1 type penalty-based sparsity settings. Figures 7(a) and (b) specifically address fixed sparsity scenarios, where the comparison reveals that models under l_1 sparsity achieve sparsity levels comparable to those subjected to group sparsity ($l_1 - l_2$). The increase of parameter sparsity in models with l_1 regularization follows a linear steady pattern. In contrast, models with $l_1 - l_2$ regularization exhibit initial volatility in parameter sparsity, characterized by quick increases or variations. This is mainly because parameter groups are collectively deactivated in the structured sparsity approach. The performance of the tasks under structured and unstructured sparsity is mostly similar, with the exceptions of a few tasks performing well in a structured setting; see Tables 1 and 2 in the Appendix for a detailed comparison of the task-wise performance.

In the case of the meta-sparsity setting i.e., Figure 7(c), it is evident that the structured sparsity gives stable sparsity patterns, while those for unstructured sparsity are highly variable with too many fluctuations. The stability could be beneficial in practical applications where consistent performance is crucial. The variability in unstructured sparsity may reflect a continuous adaptation to the learning task, which could be advantageous in non-stationary environments where the model needs to constantly adjust.

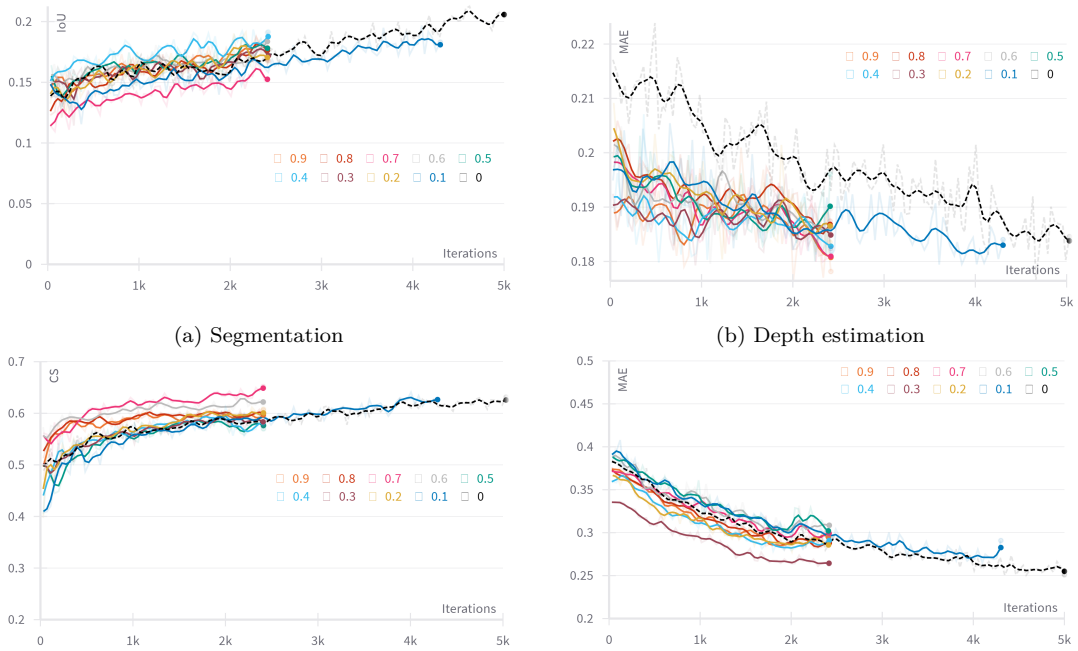
Overall, we show that the proposed approach of meta-sparsity can learn both structured and unstructured sparsity. However, the choice between these forms of sparsity depends on the specific requirements of the use case at hand. While unstructured sparsity often leads to greater model compression by zeroing out more parameters, this may come at the cost of network performance (Hoefler et al. (2021)). Structured sparsity, on the other hand, is better suited to the needs of current hardware designs. By zeroing out entire channels or filters, the sparse network architecture can be implemented more effectively on the current hardware accelerators like GPUs or specialized ASICs. When combined with hardware acceleration, structured sparsity can significantly reduce computation time. On the other hand, unstructured sparsity may not result in computational speedups without specific hardware support since the remaining non-zero values are dispersed throughout the matrix, prohibiting the efficient use of vectorized operations.

Regrowing the parameters: As discussed earlier, regrowing refers to the process of systematically reintroducing the sparsified parameters, which allows the network to recover from over-sparsification. While this concept has been outlined in Section 3, it should be noted that the empirical results presented did not involve any regrowth (i.e., $r_p = 0$). The rationale behind this was to focus our analysis on evaluating the effectiveness of the proposed meta-sparsity approach. Adding regrowth would require adjusting another hyperparameter, which could affect the clarity of our findings on meta-sparsity.

Table 7: Average performance for the four task combination i.e., (T_1, T_2, T_3, T_4) of the NYU dataset under the meta-sparsity setting for various values of the regrowth parameter, r_p. The regrow parameter, say $r_p = x$, signifies that there is a x% chance that any sparsified channel will be regrown or reintroduced. In this work, we use Xavier initialization (Glorot & Bengio (2010)) to set the new values of the regrown filters. $r_p = 0$ represents the case when none of the parameters is re-grown during meta-training.

Regrow prob. r_p	Segmentation T_1 IoU(↑)	Depth est. T_2 MAE(↓)	SN est. T_3 CS(↑)	Edge det. T_4 MAE(↓)	Parameter sparsity (%)
0 (no regrow)	0.2923	0.1397	0.7414	0.1395	44.1159
0.2	0.3177	0.1339	0.7514	0.1398	30.1157
0.4	0.3100	0.1409	0.7437	0.1405	30.0186
0.6	0.3137	0.1356	0.7500	0.1382	29.9991
0.8	0.3170	0.1351	0.7472	0.1409	31.0982

Figure 8 illustrates the subtle impact of the regrowth rate on the meta-training phase of the different tasks. It is evident from the plots that the presence of regrowth leads to faster convergence, which indicates that



(a) Segmentation (b) Depth estimation

(c) SN estimation (d) Edge detection

Figure 8: Comparison of the no-regrow (for r_p =0, in black dotted lines) vs regrow (for r_p = 0.1, 0.2, 0.3,.., 0.9) on the performance of the tasks during meta-training.

reintroducing the parameters helps the model quickly find the optimal parameters. Although there are not very significant performance gains during meta-training. The test performance of some of these models that incorporated regrowth is shown in Table 7, along with the % parameter sparsity. This table compares the no-regrow setting to the regrow settings with $r_p = 0.2, 0.4, 0.6, 0.8$. Analysis of the table reveals minimal performance improvements observed with different regrowth rates, except for the segmentation task. However, the model with regrowth is relatively less sparse than the one without regrowth. Figure 8 and Table 7 suggest that an optimal regrowth probability may exist, which balances the trade-offs between model compression and learning efficacy.

6 Conclusion and future scope

This study demonstrates that model sparsity can be a learnable attribute rather than a feature determined by heuristic hyperparameters. Our proposed framework for learned sparsity, also referred to as *meta-sparsity*, shows that models may be (meta-)trained to naturally adopt sparse structures, eliminating the need for manual tuning of sparsity levels. Our outcomes show that this strategy can produce models that are not only efficient and compact but also perform well on a variety of tasks. Although the segmentation task for the NYU dataset, in particular, poses a challenge due to its inherent complexity, such as dense pixel maps of around 40 segmentation classes, the meta-sparsity framework has proved robust. This study especially focused on the MAML framework within the context of meta-learning. However, it is acknowledged that various advanced extensions of MAML or similar gradient-based meta-learning algorithms can potentially improve performance and are viable alternatives for implementation in this work. The aim of this study extends beyond merely enhancing the performance of the tasks; it proposes a concept that could lead to the development of parsimonious models.

Theoretically, the proposed meta-sparsity approach is versatile and can be applied to any number and types of tasks, as well as various types of sparsity. In other words, it can be said that the framework is task-agnostic, model-agnostic, and sparsity-type agnostic. The key design choice lies in defining the structural groups over which regularization is applied. These groups (denoted θ^g in Eq. 5) could represent filters, neurons, attention

heads, or even task-specific decoders—making the approach highly adaptable to various architectures and objectives. Based on the experiments, we have identified a few scenarios where the method may prove to be highly effective-

- *Similar or closely related tasks:* The definition of similar tasks is very subjective; however, in the context of this work, they can consider them as tasks that may require some similar set of features. Our experiments indicate that meta-sparsity performs best when the tasks are similar or closely related, like depth estimation, surface normal estimation, segmentation, and edge detection for the NYU-v2 dataset. In such cases, the approach is better able to identify and leverage optimal shared sparse patterns that benefit all tasks involved. When tasks are highly diverse, it may be more challenging to find an optimal shared sparse pattern that effectively supports all the tasks. In such cases, the variability in the task feature requirement can make it difficult to achieve good performance for all the tasks. The performance of the task combination T_1, T_2, T_3, T_7 for celebA is one such example. While this is a known challenge in MTL, approaches such as task-grouping, task-scheduling, or task-specific sparsity mechanisms could be effective strategies to mitigate this issue, therefore, pointing to practical future research directions.
- *Inclusion of pixel-level tasks:* Adding a pixel-level task to the task mix can enhance the performance of all tasks, as observed in our experiments with the CelebA dataset ($T_1 - T_7$ vs $T_2 - T_7$, here T_1 is the only pixel level task). Pixel-level tasks require more granular features, which may also benefit image-level tasks by providing richer feature representations.

One of the key limitations of the proposed approach is the exponential growth in the number of possible task combinations used to construct learning episodes (as per Equation 9). As the number of tasks increases, this design introduces computational overhead and limits parallelization efficiency on GPUs, making large-scale applications more challenging. Addressing this issue remains a priority for future work. Possible directions include selective episode sampling, task grouping strategies, or more efficient meta-batching techniques to reduce redundancy while preserving training diversity.

Our approach represents a step towards developing *black box* sparsity, i.e., allowing models to learn an optimal sparsity pattern. This approach is not limited to a specific model, task, or type of sparsity. It is strengthened by the concept of meta-learning, which learns the sparsity pattern across a range of tasks and allows easy integration of new tasks to the sparse models. MTL facilitates the joint training of diverse tasks within a single model. When combined with sparsity, MTL not only helps with model compression but also enhances the task's performance by effective feature sharing between the tasks.

Meta-Sparsity is presented as a proof of concept—a principled framework to meta-learn sparsity in MTL settings. We acknowledge that this formulation opens the door to a number of potential enhancements. These include learning task-specific λ values, introducing hierarchical or multi-level sparsity structures, or adapting the bilevel optimization to suit architecture-specific needs, all of which could further improve performance. In continuation of this work, various directions could be pursued. A few of them are listed below:

Structured sparsity in diverse architectures: Although structural sparsity has demonstrated potential in networks with residual connections like ResNet architectures, its applicability to other networks remains unclear. Future research might examine how different types of structured or block sparsity could be customized for different network architectures.

Task transference in sparse models: Exploring task transference in sparse multi-task models is a promising direction for further research. Investigating the sparse features that promote better sharing across tasks could provide new insights into multi-task networks and the impact of sparsity on cooperative learning.

Hardware efficiency of sparse models: It is also necessary to investigate how sparse models align with present and upcoming hardware capabilities. The aim is to translate model compression due to sparsity into tangible computational efficiency and speed improvements on different hardware platforms.

Task-aware sparsity control: Future work could explore methods for learning task-specific sparsity levels (e.g., task-wise λ) or incorporating task-grouping and scheduling strategies to better align shared representation with task similarity.

Meta-sparsity beyond MTL: Investigate alternative meta-optimization techniques suitable for STL and non-episodic training, including online bilevel optimization and self-supervised sparsity regularization frameworks.

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